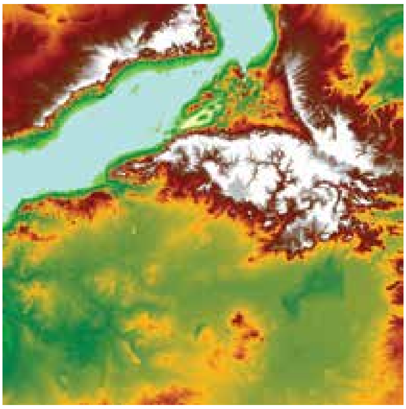
ISSN 1810-1119

15

FAO ANIMAL PRODUCTION AND HEALTH



manual

CONDUCTING NATIONAL FEED ASSESSMENTS

15

FAO ANIMAL PRODUCTION AND HEALTH
manual

CONDUCTING NATIONAL FEED ASSESSMENTS

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 2012

Recommended Citation

FAO. 2012. *Conducting national feed assessments,* by Michael B. Coughenour & Harinder P.S. Makkar. FAO Animal Production and Health Manual No. 15. Rome, Italy.

Authors

Michael B. Coughenour
Natural Resource Ecology Laboratory
Colorado State University, Fort Collins, Colorado, USA.
mikec@nrel.colostate.edu

Harinder P.S. Makkar
Animal Production Officer
Animal Production and Health Division
FAO, Rome, Italy
Harinder.Makkar@fao.org

ISBN 978-92-5-107332-2

Contents

Foreword v

Acknowledgements vi

Acronyms vii

Introduction x

Aim and structure of this manual - a road map xv

SECTION I
State of Knowledge **1**

1 Trends in demand for feed **3**

2 Assessing feed supplies in relation to increasing demands **7**

3 A summary of case studies on national, regional and global feed assessments **11**

SECTION II
Methodologies and Guidelines **23**

4 A synthesis of methodologies available for national feed assessments **25**

5 Guidelines for the development of National Feed Assessment Systems (NFASs) and the implementation of National Feed Assessments (NFAs) **35**

6 References for Sections I and II **51**

SECTION III
Case Studies **57**

7 Demand growth for animal-source foods: Implications for livestock feed production **59**

8 The Swiss feed balance **67**

9 The Indian feed inventory **75**

10 Pastoral surveillance system and feed inventory in the Sahel **83**

11 Development and application of Earth observation-based rangeland monitoring techniques in Namibia **95**

12 Gobi Forage Livestock Early Warning System **115**

13 Livestock feed inventory on the Tibetan Plateau by remote sensing and *in situ* observation **131**

14 The development of feed balances for Livestock **143**

15 The use of ecosystem simulation modelling to assess feed availabilities for large herbivores in heterogeneous landscapes **151**

16 Technologies, tools and methodologies for forage evaluation in grasslands and rangelands **165**

Foreword

Demands for foods of animal origin are increasing globally, due to increasing population growth, urbanization and income growth. The limits of existing livestock production systems are being approached, if not exceeded, because of increased demands for livestock feeds vis-à-vis availability. Accurate assessments of current and future supplies and demands for livestock feed are needed for national food security policy and planning, as well as the setting of environmentally sustainable stocking rates. National feed resources must be assessed and monitored to provide information that is useful for the development and implementation of appropriate policies that will contribute to the sustainable growth of national livestock sectors.

A wide range of livestock feed situations exists across different countries, environments and livestock production systems, ranging from spatially extensive pastoralist systems to intensive systems consisting of mixtures of crops and livestock, and extremely intensive and landless production systems in which livestock are fed entirely with transported feed. Crop-based livestock systems have the most people, the most livestock, and are the most productive. In these systems, there is a need for continuing assessments of feed resources in support of more efficient and environmentally-friendly land use and improved livelihoods. These are diverse and complex systems with wide arrays of feed sources and types that must be quantified using diverse data from household surveys, agricultural statistics, markets and land use studies. In contrast, spatially extensive systems require livestock movements over large areas of relatively low productivity in environments where crop-based agriculture is not feasible. In these environments, remote-sensing data must be combined with modelling and ground data to monitor forage production over large, heterogeneous and often remote areas.

The aim of this manual is to provide guidance and tools to countries in developing National Feed Assessments (NFAs), based on what has already been learned from current approaches across a wide range of feed situations. Global and country level feed situations are reviewed to highlight the needs for quantitative assessments of livestock feeds in both developed and developing countries. Broad guidelines for the development of NFAs are provided, followed by detailed case studies and descriptions of methodologies that have been implemented in a variety of countries world-wide. The case studies include examples of spatially intensive and spatially extensive production systems, and examples from highly developed as well as developing countries. Based on inputs from a group of experts who met in Rome in November 2010, a set of recommended stepwise procedures is given for implementing NFAs, including procedures for their planning, establishing and updating.

Berhe G. Tekola
Director
Animal Production and Health Division

Acknowledgements

The lead authors would like to thank all those who contributed so diligently and excellently to the content of this document. We would also like to acknowledge and thank participants of the Experts Meeting in Rome, November 2010, including the contributors to this document, and also the following participants who could not contribute to the document directly: Pedro Argel, Gonzalo Mata, William Thorpe and Bruce Pengelly. We thank Badi Besbes, Mark Powell, Datta Rangnekar and Ghulam Habib for their thorough and valuable reviews and editorial inputs. Thanks are also due to Philippe Ankers for critical comments and suggestions, which improved the document substantially. We also wish to thank Samuel Jutzi and Simon Mack for their support to this work.

Acronyms

ACF	Action Contre la Faim
ACU	adult cattle unit
ADDS	Africa Data Dissemination Services
AGB	aboveground biomass
ALMANAC	Agricultural Land Management Alternatives with Numerical Assessment Criteria
ANPP	aboveground net primary productivity
APEX	Agriculture Policy/Environmental Extender Model
ARIMA	auto-regressive integrated moving-average
ARTEMIS	Advanced Research & Technology for Embedded Intelligence and Systems
ASF	animal source food
AUM	animal unit month
AVHRR	Advanced Very High Resolution Radiometer
CMORPH	Climate Prediction Center Morphing Product
CNRIT	Center for Natural Resource Information Technology
CPC	Climate Prediction Center
CR	crop residue
DE	digestible energy
DEM	digital elevation model
DPM	disc pasture meter
DMI	dry matter intake
DMP	dry matter productivity
EDYS	Ecological Dynamics Simulation Model
EVI	enhanced vegetation index
EWS	early warning system
FAO	Food and Agriculture Organization
FCR	feed conversion ratio
FAPAR	fraction of absorbed photosynthetically active radiation
FNIRS	faecal NIRS (near infrared reflectance spectroscopy)

FPAR	fraction of photosynthetically active radiation
GDAS	Global Data Assimilation System
GDP	gross domestic product
GIS	Geographic Information System
GL-CRSP	Global Livestock Collaborative Research Support Program
GLC	global land cover
GPP	gross primary production
GPS	Global Positioning System
GRUMP	Global Rural Urban Mapping Project
GTS	Global Telecommunications System
HANPP	human appropriation of net primary production
HRPT	High Resolution Picture Transmission
HSI	Habitat Suitability Index
IMPACT	International Model for Policy Analysis of Agricultural Commodities and Trade
KRA	key resource area
LARST	Local Application of Remote Sensing Technology
LEAD	Livestock, Environment and Development
LEWS	Livestock Early Warning System
LSWI	Land Surface Water Index
ME	metabolizable energy
MODIS	Moderate Resolution Imaging Spectroradiometer
MSS	multispectral scanner
NAMHEM	National Agency for Meteorology, Hydrology and Environment Monitoring
NAPP	net annual primary production
NASA	National Aeronautics and Space Administration
NASA-GSFC	National Aeronautics and Space Administration - Goddard Space Flight Centre
NCFR	non-conventional feed resource
NDVI	Normalized Difference Vegetation Index
NE	net energy
NFA	National Feed Assessment
NFAS	National Feed Assessment System
NGO	non-governmental organization

NIR	near infrared
NIRS	near infrared reflectance spectroscopy
NOAA	National Oceanic and Atmospheric Administration
NOAA AVHRR	National Oceanic and Atmospheric Administration Advanced Very High Resolution Radiometer
NOAA-HRPT	National Oceanic and Atmospheric Administration - High Rate Picture Transmission
NPP	net primary production
NPV	non-photosynthetic vegetation
PAL	Pathfinder AVHRR Land
PAR	photosynthetically active radiation
PDA	personal digital assistant
PHYGROW	Phytomass Growth Simulator Model
RIAH	Research Institute for Animal Husbandry
SCS	Soil Conservation Service
SLAM	Spatial Livestock Allocation Model
SOM	soil organic matter
SUA	supply utilization account
TOMS	Total Ozone Mapping Spectrometer
USAID	U.S. Agency for International Development
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
USLE	Universal Soil Loss Equation
VI	vegetation index
VIUPD	vegetation index based on universal pattern decomposition
VPI	Vegetation Productivity Indicator
VPM	Vegetation Photosynthesis Model
WCA	World Census of Agriculture
WEPP	Water Erosion Prediction Project
WMO	World Meteorological Organization

Introduction

WHAT ARE NATIONAL FEED ASSESSMENTS AND NATIONAL FEED ASSESSMENT SYSTEMS?

Simply stated, a *National Feed Assessment (NFA)* is a data- and computation-based analysis of the supplies and demands for livestock feeds in a country, where livestock includes all beef and dairy cattle, sheep, goats, buffalo, swine, equines and poultry. Human foods include a substantial complement of livestock products which are, in turn, derived from a wide variety of plant-based feeds that are consumed by livestock. National agricultural statistics are used to assess food security, but these statistics have often just included statistics for livestock-based food supplies and have fallen short in assessing supplies of plant materials which are needed to support the livestock. An NFA bridges this gap by determining the total quantities of feed available to the livestock relative to the demands of the livestock for feed. Thus, both the supplies and the requirements for feed must be calculated. This is a complex task because livestock feeds are highly diverse and often poorly quantified; they are either not directly measurable commodities or are widely distributed over extensive grasslands and other rangeland environments which are poorly monitored, if at all.

A *National Feed Assessment System (NFAS)* is a complete set of procedures, facilities, tools, personnel, organizations and institutions involved in the collecting, handling and processing of data necessary to calculate and report the supplies of livestock feeds from all sources and for all livestock types in a country. It is a system in the sense that it is more than the mere sum of its parts; it comprises numerous components which interact in an integrated manner to achieve a common outcome – a National Feed Assessment.

WHY DO WE NEED NATIONAL FEED ASSESSMENTS?

Population growth, urbanization and income growth are driving enormous increases in demand for foods of animal origin. The limits of existing livestock production systems are being approached, if not exceeded, due to increasing demands for livestock feeds vis-à-vis availability. The situation is particularly acute in developing countries. The increasing demand for livestock products has far-reaching implications for human well-being, socio-economics, land use, the environment and animal health. Accurate assessments of current and future supplies and demands for livestock feed are needed for national food security policy and planning, as well as the setting of environmentally sustainable stocking rates. Feed resources must be assessed and monitored to provide information for the development and implementation of policies that will contribute to the sustainable growth of national livestock sectors. Assessments will provide information on feed resource availability that will enable optimal policy decisions regarding the use of national feed resources.

Information provided by livestock feed inventories would be of immense utility for policy-makers, government agencies, non-governmental organizations (NGOs), intergovernmental agencies and development agencies in formulating and implementing sustainable livestock development activities and for preparing and coping with climatic variations such as droughts, floods, severe winter weather events and global climatic change. Spatial and temporal assessments of current and forecasted feed resources, including forage, will assist in disaster management and policy-making. Feed assessments would also inform decisions related to the nature and quantities of commodities, the feed resources that could be traded locally, potential areas for feed markets and feed resources involved in imports and exports. Estimates of feed resources and demands are needed to assess the fractions of food grain that are used for feed.

Although livestock feed shortages have clearly constrained productivity in many countries, the impacts of feed shortages at national levels have been poorly characterized due to the lack of national scale feed assessments. In addition, information on the availability of feed ingredients at the country level will enhance the efficiency and profitability of the animal feed industry and assist researchers to formulate sustainable feeding strategies. Such information would also be useful for determining the input-output relations for countries such as the estimation of edible protein outputs versus protein inputs. Estimates of feed resources would also improve the accuracy of assessments of the environmental impacts of livestock resulting from land use transformations as well greenhouse gas emissions and element fluxes (e.g. nitrogen) associated with livestock production. Production and consumption of feeds would significantly affect the potential of ecosystems to sequester carbon. Country-level feed balances based on feed inventory data will facilitate planning within the livestock industry, for example in determining how many animals can be supported or produced based on existing feed resources, and in identifying what feed resources would and could be developed to achieve production objectives. Such efforts will, in turn, translate into enhanced food security balanced with environmental sustainability.

There is a wide spectrum of livestock feed situations globally and within individual countries, varying from intensive use of crop-based feeds and pastures to spatially extensive use of grasslands and rangelands. Land availability and water are key constraints on the production of alternative feeds for ruminants in the most intensive systems. A structured approach to planning for this increase in demand will be necessary if demand is to be met cost-effectively, with minimal social disruption and minimal environmental impacts. In arid and semi-arid regions, pastoralists graze their livestock in spatially extensive grazing systems characterized by large-scale seasonal movements. Livestock forage production is highly limited by rainfall, which is spatially and temporally variable. Knowledge of forage biomass availabilities and distributions can assist pastoralists in determining whether to move, buy or sell animals, and assess the level of risk for decision-making. Feed assessments are needed to provide useful information for food aid organizations, pastoralists, governments and development agencies.

The prospect of increasing feed demands raises the serious question of how these additional livestock feed requirements will be provided. Systematic approaches for accurately assessing livestock feed supplies are relatively undeveloped compared with long-standing programmes that inventory agricultural productivity (e.g. FAO, 1994, 2010). Furthermore, the quantification of livestock feeds has proved to be more challenging than the quantification of total crop production for a number of reasons. Data needs and complexities increase with the addition of another trophic level. Data are needed for the production of numerous derived feedstuffs and the availabilities of forage for livestock. Many crop residues and by-products used for forage are not quantified because they have no direct market value. Many additional, but poorly quantified factors, constrain access to forage in spatially extensive rangelands and grasslands.

Recently, the Livestock Data Innovation in Africa Project administered an online survey among livestock stakeholders to identify core livestock domains/areas for which livestock information is demanded (Pica-Ciamarra *et al.,* 2012). The survey had 641 respondents. Within governments livestock data and indicators are used for three main purposes, including policy and planning (44 percent), development projects (33 percent) and research (30 percent). NGOs/Donors/International Organizations use data/indicators primarily to design and implement development projects (31 percent); private companies to formulate investments (76 percent); researchers for research purpose (67 percent) and to formulate and implement development projects (39 percent). Out of 15 different livestock data types, data on livestock feeds was ranked fourth in importance, behind animal health, meat production, and livestock population. Milk production was fifth. Respondents also ranked various data types according to needs for improvements in data quantity and quality. Livestock feed data was ranked third in needs for improved data.

Based on an assessment of the current global livestock feed situation, as presented in this Manual, it is clear that global feed resources, especially those which will support the rapidly growing, intensive production systems of the developing world, must be assessed and monitored to provide information that is useful for the development and implementation of appropriate policies that will contribute to the sustainable growth of the global livestock sector. Assessments will provide information on feed resource availabilities that will enable optimal policy decisions regarding the use of these resources. The assessments should enhance the development of optimal feeding strategies and thus food security, the ability to cope with emergency feed shortage situations, the ability to provide input data into country level food input-output analyses, and the capability to assess environmental impacts of livestock.

A wide range of livestock feed situations exists across different countries, environments and livestock production systems (Thornton *et al.,* 2002, 2003, 2006). An overarching gradient exists from spatially extensive pastoralist systems to increasingly intensive systems consisting of mixtures of crops and livestock, and to extremely intensive and landless production systems in which livestock are fed entirely with transported feed. The spatially extensive systems are typically found in arid and semi-arid environments, or in environments that are thermally limited with short growing seasons.

Spatially extensive systems require livestock movements over large areas of relatively low productivity in environments where crop-based agriculture is not feasible. It has been difficult to assess forage availability in such environments due to the difficulty of forage production monitoring over large, heterogeneous and often remote areas. Moreover, forage production is an insufficient measure of forage availability in such environments because availability is constrained by drinking water, topography and other factors that affect livestock movements. Temporal variability of feed availability in such environments is highly important, as feed availability varies with seasons and with variations in precipitation, snow cover, and water availability. Food security in these environments is often jeopardized by droughts or severe winter weather conditions. These systems are being altered by increasing competition for land, sedentarization and restrictions on mobility. In such environments, there is a need for livestock feed assessments that can quantify forage biomass over large areas while accounting for temporal variability and constraints on feed availability.

Crop-based livestock systems have the most people, the most livestock, and are the most productive. Crop-based systems are facing increasing demands for food, especially animal source foods and increasing human and livestock populations. As such, they are dynamic. Also, crop-based livestock systems can be in direct competition for land where crops are being grown for human food production. Increasingly, livestock systems are making use of crop residues and other agricultural by-products which are often difficult to quantify. These are diverse and complex systems with a wide range of feed sources and types. The intensity of land and resource use in such systems presents challenges for environmental sustainability. In these systems, there is a need for continuing assessments of feed resources in support of more efficient and environmentally-friendly land-use and improved livelihoods.

Spatially extensive and crop-based systems are both dynamic, and it will be important for feed assessments to capture trends. Feed assessments will only be useful if they address the dynamism of the systems themselves (i.e. modes of operation), as well as the dynamism of feed production and utilization. Capturing trends will, therefore, be very important, both looking back and, most importantly, anticipating change and its implications. Consequently, an important output of a feed assessment system will be a trend analysis, synthesizing results of the current assessment compared with past assessments. Observed trends must be analysed and explained. Other changes that are caused by unpredicted driving forces should also be identified and assessed.

WHO WILL DEVELOP NATIONAL FEED ASSESSMENT SYSTEMS?

The development of a National Feed Assessment System (NFAS) must include people with expertise in a wide variety of relevant subject matter regarding livestock production systems in a broad range of environments and settings, as well as people with expertise in the procedural and organizational aspects of implementing national-scale database systems. Technical expertise will be needed in various aspects of livestock and feed production systems, agriculture, grassland and rangeland ecology, agricultural statistics, and spatial databases. Stakeholders who are affected by various aspects of livestock feed production activities and feed availabilities must also be involved, including livestock producers, pastoralists, feed producers, NGOs, as well as government ministries, researchers and academicians. Stakeholders and partners will be central in the implementation of a NFAS because they will undoubtedly play a variety of important roles in its ongoing operation and utilization. They may, for example, be data providers or facilitators of data sources. They will also play a role in its institutionalization.

Task forces or working groups can be formed from the pool of people with this wide range of expertise and interests. This will include: a) people with skills and knowledge in agricultural resource statistics and agricultural systems analysis; b) people with extensive knowledge of rangeland and crop-based livestock production systems, and animal nutrition; c) people with technical capabilities in geographic information system (GIS) analysis, remote sensing, ecological and agricultural modelling, database design, statistics, sampling and surveys; d) people with multi-disciplinary expertise, that is, with broad, large-picture, integrative, systems-level perspectives; e) people from farmers' or livestock keepers' associations and pastoral NGOs; f) people from government ministries overseeing agriculture, land use and the environment; g) people from the private sector who are involved in feed production; h) people from NGOs and research institutions who have relevant experience; and i) proponents, including individuals, who are in a position to push the implementation forward with respect to government institutions and other potential end user groups.

An institutional framework must be created. The institutional framework of the NFAS may comprise a single NFAS organization or a coalition of organizations with diverse roles and responsibilities. The institutional framework will be the backbone of the NFAS. It will ensure that there are mechanisms to maintain the necessary infrastructure for its continued application. Institutionalization will require: a) the identification of the national implementing partner; b) the establishment of an institutionalized coordinating team at a national or possibly regional level: c) the establishment of a state and/or central government budget line to support the system, along with capabilities for the necessary mobilization of resources, capital and recurrent expenditures; and d) the establishment of a regional training programme for staff who will implement the system, as well as end users who will use the outputs of the NFAS.

Members of governments and research organizations who wish to establish national feed assessment systems will likely seek guidance on the technical issues and procedural aspects involved. This document aims to provide such guidance.

Aim and structure of this manual – a road map

The aim of this document is to provide guidance to countries in developing NFAs, based on lessons learned from current approaches across a wide range of feed situations. Although feed inventories are the primary components of NFAs, the concept of an assessment is broader because it considers the causes and consequences of variability in feed supplies, balances between feed supplies and requirements, and other implications of feed quantity and quality.

The document has three major sections. Sections I and II may suffice for most readers; those interested in more detail can refer to Section III.

Section I provides a broad perspective of the current state of knowledge on the livestock feed situation. Chapter 1 sets the stage by providing an overview of global trends in livestock-based foods and Chapter 2 continues with an overview of subsequent growth in livestock feed requirements. Chapter 3 summarizes assessments of the livestock feed situations for a number of country, regional and global case studies, most of which are described in detail in subsequent chapters of this document (Chapters 8–13).

Section II contains a synthetic overview of methodologies and guidelines for implementing NFAs. It is suggested that the reader refers to this Section before going to Section III. Chapter 4 covers approaches for calculating growth in livestock feed requirements, methods for assessing feed supplies in crop-based and spatially extensive grazing systems, tools specifically utilized in rangeland systems, methods for assessing feed balances, data base methods and data sources. A section on environmental considerations is also included, given that any assessments of feed availabilities are contingent on potential interactions with alternative land uses and impacts on ecosystem services. Chapter 5 provides stepwise guidelines for the procedural and organizational aspects of planning, establishing and updating a National Feed Assessment System (NFAS). These recommended procedures for implementing a NFAS are based on inputs from a group of experts who met in Rome in November 2010.

Section III contains the detailed descriptions of the case studies summarized in Chapter 3 and the methodologies described in Chapter 5. The case studies are specific examples that could assist countries desiring to establish a NFAS. Methodologies are described, along with example implementation, data inputs and NFAS outputs. Chapter 7 describes an approach for calculating the growth in demands for livestock-based food and livestock feeds at national through global levels. Chapters 8–13 are in-depth case studies of recent approaches to assessing livestock feed situations in a wide variety of countries or regions with markedly differing socio-economic and biophysical environments. The Switzerland case study is an example of a NFAS in a highly developed country with well-developed agricultural statistics and data bases, and a preponderance of well-defined crop-based feeds but also with important pasture resources. The India case study demonstrates the challenge of assessing livestock feeds in a highly diverse environment with less developed national agricultural statistics and databases. India contains a very wide variety of mixed crop-livestock systems and highly intensive utilization of all forms of potential livestock feeds, many of which are difficult to quantify because they are normally not included in national agricultural statistics. These two NFASs are especially capable of assessing livestock feeds from crops or mixed crop-livestock production systems.

These are followed by four examples from "spatially extensive" systems in Africa and Asia where national agricultural statistics would be of little use due to the primary dependence on non-crop-based resources in grasslands, savannahs and other types of rangelands. In these systems the only source of data over such vast areas is from satellite-based sensors orbiting high above the Earth's surface, Chapter 14 presents a relatively detailed methodology for calculating livestock feed balances, the central part of which is the calculation of livestock feed requirements based on livestock energy requirements, digestive efficiencies and the energetic characteristics of feed sources. Chapter 15 describes a comprehensive ecosystem modelling approach that can be applied to spatially heterogeneous and extensive livestock systems. The ecosystem modelling approach is the most demanding, but it also integrates the full range of factors involved in the livestock feed assessment, including calculations of spatially and temporally varying feed availabilities along with calculations of livestock feed requirements and actual intake rates on various parts of the landscape. The modelling approach is also prognostic, in the sense that predictions can be made on the basis of changes in climatic and other environmental conditions. Chapter 16 is a detailed description of methodologies for forage evaluation in grasslands and rangelands, from field-based approaches for measuring forage quantity and quality, to systems which utilize satellite and weather data over regional spatial scales, and to ecosystem modelling approaches.

SECTION I

State of knowledge

1. Trends in demand for feed

In the developing countries, consumption of meat has been growing at over 5 percent annually in the last few decades and is expected to grow by 1.4 percent per year worldwide to 2030 (FAO, 2006a). In energetic terms, consumption of meat increased more than threefold that observed in developed countries from 1971 to 1995 (Delgado *et al.,* 1999). A major reason for the increase is that consumption has been rapidly growing in a number of large countries including Brazil, China and India (FAO, 2006a). Poultry production and consumption has been growing at more than 5 percent annually and is an increasing fraction of mean world production, from 15 to 30 percent over the last three decades. By 2050, 2.3 times as much poultry meat and between 1.4 and 1.8 times as much that of other livestock products will be consumed as in 2010 (FAO, 2006a; FAO, 2011). In India, the demand for poultry is expected to increase 844 percent by 2030, which translates to 8 865 400 tonnes of poultry products. This will require over 27 million tonnes of feed and an additional 24 million hectares of crop land unless the proportion of by-products and non-conventional resources in feed increases substantially and/or the contribution of backyard scavenging birds to poultry production increases (Chapter 7). Consumption of livestock products is closely related to per capita income. As incomes in many developing countries have grown rapidly over the last 20 years, consumption levels of meat and other animal products have also increased (Steinfeld *et al.,* 2006). Increases in income will encourage higher consumption per person, particularly in the developing world (FAO, 2011). As a result, total consumption in developing countries will eventually exceed consumption in the developed countries.

In Asia, human demands for animal source foods are beginning to outstrip production, with projections of two to threefold higher demand in 2050 in most countries (Devendra and Leng, 2011). These authors also point out that limited supplies of inexpensive grain feeds will drive more intensive use of forage, crop residues, agro-industrial by-products and non-conventional feed resources, and there will be an increased focus on making maximum use of crop residues and low quality roughages. They suggest that the two billion tonnes of straw the world produces could be converted into animal products with a feed conversion efficiency of about 10:1 to produce 200 million tonnes of live animals annually which could support four billion people.

In much of the developing world, mixed crop-livestock systems are prevalent. These are systems in which livestock are intimately tied to crop production through their use of crop residues, livestock recycling of nutrients and use of livestock for draft power (Herrero *et al.,* 2010). According to their analysis, mixed systems produce almost 50 percent of the world's cereals and most of the staples consumed by poor people, 41 percent of maize, 86 percent of rice, 66 percent of sorghum and 74 percent of millet. They also produce 75 percent of the milk and 60 percent of the meat, and employ many millions of people. Some crops such as maize, wheat, sorghum and millet are dual purpose – their grain provides food for humans and their residues are used as feed for livestock.

Livestock systems are intensifying. There is an increasing intensity of feed grain use, along with increased use of protein rich feeds and additives that enhance feed conversion. Meanwhile, traditional feed utilization is in decline (Steinfeld *et al.,* 2006). Historically, the use of grain to feed animals has primarily been a practice of developed countries. For example, 40 percent of cereals are used for livestock feed in the United States, while only 14 percent are used for feed in Africa. Additionally, while animal source food (ASF) consumption is very high, perhaps excessive, in the developed world, there is considerable room for increased incorporation of ASFs into diets in the developing world to improve nutrition (Speedy, 2003). There has also been a shift of world livestock production out of regions that use grain-intensive feeding systems into developing countries where grain is less important as a feed. However, it is quite likely that the opposite trend will occur – that continued growth of livestock production in developing countries will be associated with shifts to more intensified systems making greater use of cereals (FAO, 2006a). It has also been suggested that in developing countries, increased demand for food crops will compete with increasing demands for livestock feed, so substantially more feed grains will have to be imported (Delgado *et al.*, 1999). Due to increasing human populations in south Asia, intensive mixed systems will have to attain all their production from alternative feed sources apart from stovers, because stover feeding only meets animal maintenance requirements (Herrero *et al.,* 2009).

China has experienced a very large growth in demands for dairy products due to rises in income, changes in urban lifestyles and overall development of the dairy sector (Simpson, 2006). Milk consumption per capita tripled from 1985 to 2000, then doubled from 2000 to 2004. If China develops further, there will be an increasing shift to modern dairy farms, which will benefit from advances in genetic, breeding and dairy management worldwide. A pressing issue is the extent to which the dairy industry will be able to meet future demands. This leads to the question of whether China can provide sufficient feedstuffs for the growing dairy industry. A complex model-based assessment of these questions (Simpson, 2006) concluded that protein-based feedstuffs will increasingly have to be imported, while energy-based feedstuffs exist in abundance. Importantly, the assessment considered the fact that each country feeds its animals according to resource availabilities, tastes and preferences, and comparative advantages in production of feedstuffs (Simpson, 2010a). China will not, as many assume, move towards the large-scale feedlot systems typical in America, for example. A large fraction of national energy-based livestock feeds will be derived from crop residues (38 percent) and crop by-products including silage (21 percent). An even larger fraction of protein feedstuffs will be derived from crop residues (28 percent) and by-products (48 percent). By-products, non-conventional feeds and forages will continue to constitute a substantial portion of feedstuffs for dairy cows in much of China over the next decade, especially in the less populated areas. Consequently, considerable attention must be paid to assessing the stocks and flows of these feed sources.

Given the ongoing and expected future increases in animal source food consumption, there is increased controversy as to whether cereals and other foods that humans can eat could be fed to livestock (Speedy, 2003). While some argue that increased demand for animal source foods will increase demand for grains used for humans, livestock can consume crop products that otherwise would become waste or they can be raised on land that has no crop-based agricultural potential (Delgado *et al.,* 1999). Land availability and water will be key constraints to the production of alternative feeds for ruminants in the most intensive systems (Herrero *et al.,* 2009).

2. Assessing feed supplies in relation to increasing demands

The needs for developing national feed inventory or assessment systems vary among countries. In Switzerland, for example, feed inventories were developed out of strategic necessity during the World Wars to ensure continued food security (Chapter 8). Today, the need for continued food security still necessitates the acquisition of information that is necessary for coping with unplanned situations that could lead to food shortages, including droughts and disruptions in transport and shipping. Other uses have since arisen, including uses in calculations of national economic, biomass, nutrient and greenhouse gas fluxes.

Few countries in Asia have endeavoured to carry out quantitative or even qualitative assessments of feed availability, probably due to inadequate methodology and understanding of assessment approaches (Devendra and Leng, 2011). Assessments have been attempted for Peninsular Malaysia (Devendra, 1982), the Philippines (unpublished citation in Devendra and Leng, 2011), and oil palm areas in Southeast Asia (Devendra, 2009). Feed balances have been developed to assess availability and requirements in India and Pakistan (Mudgal and Pradhan, 1988; Raghavan, Krishna and Reddy, 1995; Ramachandra *et al.*, 2007) as well as Nepal (Shrestha and Pradhan, 1995).

Livestock feed shortages have clearly constrained productivity in India, as shown in numerous site-specific studies (Chapter 9; Ramachandra *et al.*, 2005; Raju *et al.*, 2002; Anandan *et al.*, 2005). However, the impacts of feed shortages at a national level have been poorly characterized due to the lack of national-scale feed assessments. A notable characteristic of Indian livestock is that almost its entire feed requirement is met from crop residues and by-products: grasses, weeds and tree leaves gathered from cultivated and uncultivated lands; and grazing on common lands and harvested fields (Dikshit and Birthal, 2010). Use of crop residues increased by 65 percent between 1980–81 and 2002–03 (Ramachandra *et al.,* 2005).

Livestock feed inventories in India, would be useful for policy-makers, government agencies, NGOs and development agencies. The information such inventories provides can be used in formulating and implementing meaningful livestock development activities and tackling natural calamities such as drought and floods (Chapter 9). Such information would also be useful for making informed decisions relevant to the nature and quantities of commodities, the feed resources that could be traded locally, potential areas for feed markets, and feed resources involved in imports and exports. Estimates of feed demand could help resolve the controversy regarding estimates of the fraction of food grain that is used for feed, which vary widely (Dikshit and Birthal, 2010). Estimates could also be used to determine the input-output relations for the livestock sector and to estimate greenhouse gas emissions associated with livestock production. Ramachandra *et al.* (2005) recommended a national feed balance approach that recognizes regional differences in livestock systems, along with a national networking system on crop and animal statistics, and the establishment of a Directorate of Animal Feed Resources Bureau to create the necessary databases and to plan and implement feed resource utilization at the national level.

Sources of livestock feeds have been identified and inventoried in Pakistan. Crop residues, cultivated fodder, grazing and concentrates contribute 57 percent, 18 percent, 19 percent and 6 percent respectively, to national livestock feed supplies (Habib, 2010). Mixed crop-livestock farming systems are widespread. After grain harvesting, crop by-products such as straws and stovers are stored and saved for year-round livestock feeding. Fodder is cultivated on a limited land area of 2.45 million hectares or 11.1 percent of the total cultivated area. Over the last two decades, fodder land has progressively decreased while fodder production has increased by up to 13 percent, apparently due to improved farmer practices (Habib, 2010). Grazing lands cover more than 20 million hectares in Pakistan, yet only contribute 19 percent of the biomass and 30 percent of the crude protein (Habib, 2010) to the total feed supply. The production potential of grazing lands has clearly declined, but the extent of the decline has been poorly quantified. Uncontrolled grazing and recurrent drought have considerably reduced their carrying capacity. Large influxes of sheep flocks from Afghanistan have placed further pressure on grazing lands. Community herd grazing at the village level, once a common practice in rural areas, has almost discontinued and farmers now graze individually. This has made it more difficult to implement rotational grazing/restricted grazing practices for protecting vulnerable rangelands. The century-old "nagha system" of restricted grazing, designed to protect common grazing lands from uncontrolled free grazing, no longer exists, or is practised to a very limited extent (Ghulam Habib, pers. comm.).

In the Africa Sahel, pastoralists graze their livestock in spatially extensive grazing systems characterized by large-scale seasonal movements among pastures as well as intra-seasonal grazing orbits in proximity to water sources (Chapter 10). Livestock forage production is limited by rainfall, which is highly variable. Pastoral livestock movements are responsive to variable distributions of forage in space and time. Periodic droughts are intrinsic to the system, leading to shortages of forage for livestock and food insecurity for pastoralists. The spatially extensive and time-varying nature of the forage resource, coupled with constraints on livestock movements created by water distributions, topography and infrastructure, necessitates an approach that is very different from the approach to assessments of livestock feed. The use of remote-sensing data, particularly of green vegetation biomass, has proved to be the only feasible approach. Thus, famine early warning systems utilize remotely-sensed greenness indices. The system described in Chapter 10 provides useful information for food aid organizations, pastoralists, governments and development agencies.

Similar situations exist in southern Africa, where a significant proportion of the human population is dependent on livestock for livelihoods and food, and where most of the livestock obtain their forage from rangelands (Chapter 11). The high spatial and temporal variability of forage production necessitates monitoring over broad spatial scales on a regular basis throughout the growing season.

An understanding of forage biomass availability across the landscape can assist Mongolian pastoralists make decisions about whether to move, buy or sell animals, and assess the level of risk for decision making (Chapter 12). However, extensive information about forage distributions over large remote areas is difficult, if not impossible to acquire. As much as 35 percent of Mongolia's livestock were lost during droughts and severe winters from 1999 to 2001. In response, the U.S. Agency for International Development (USAID) supported the development of a Livestock Early Warning System (LEWS) for the Gobi Region that provides near real-time spatial and temporal assessments of current and forecasted forage conditions. This information is provided to herders and to local and national government agencies to assist in drought management, disaster preparedness and agricultural policy-making.

The Tibetan Plateau is another example of spatially extensive pastoralism in remote and heterogeneous landscapes (Chapter 13). The human and livestock populations of the Tibetan Autonomous Region have both more than doubled over the last 40 years, resulting in increased demands on natural resources. Increased pressure, including livestock overgrazing and droughts, have resulted in grassland degradation and desertification, decreasing the available resource base and exacerbating the pressure. Thus, a livestock feed inventory would be useful in determining the availability of forage resources in relationship to demands. Such information would be relevant to food security policy and planning, as well as to the setting of sustainable stocking rates and environmental protection. Due to the expanse and remoteness of most of the pastoral grazing areas, and the challenges of working at a high altitude, low oxygen environment, ground-based field data on grassland productivity are very limited. A feed inventory for such a spatially extensive pastoral region must therefore employ remote-sensing data to the greatest extent possible.

A workshop held in 1985 in Nairobi brought together a number of scientists to assess feed resources for small-scale livestock holders in Africa (Katigele *et al.,* 1987). Although dated, it is instructive to observe the various approaches used to assess livestock feeds in developing countries at the time. In general, the assessments involved examinations of various types of feed resources such as natural grasslands (rangelands), improved pastures, cereals and root crops, and agricultural by-products. Typical total crop productivities and estimates of total cropped areas were reported based on a variety of government and Food and Agriculture Organization (FAO) statistics. However, little was done in the way of determining what was actually available to livestock. Similarly, typical values of plant production in rangelands were often presented, but quantitative inventories were not attempted, no doubt due to a lack of data across large and heterogeneous areas. Today, we have access to vastly improved databases, GIS, remote sensing and modelling capabilities. Yet, the potential of these information sources and technologies to develop national-scale feed assessments has barely been tapped.

3. A summary of case studies on national, regional and global feed assessments

3.1 SWITZERLAND

The Swiss feed balance

Switzerland has been carrying out regular feed inventories since 1933 with revisions to the methodology in 1980 and 2009 (Chapter 8). The Swiss approach is highly evolved, benefitting from experience, technical capabilities, and rich and well-organized sources of fundamental input data. A wide range of feed sources is considered, including both intensive crop-based and extensive grassland-based systems. Livestock considered include cattle, sheep, goats, pigs, poultry and horses.

Annual feed availability is calculated for a year from an inventory of domestic feed production, including crops and agricultural by-products. Availability is corrected for national feed imports and exports. Availability is expressed in terms of digestible or metabolizable energy and protein, using best available forage quality data.

As a check, animal demands for feed are calculated on the basis of livestock census data and animal energy and protein requirements. Differential requirements of breeding, fattening and milking animals are distinguished. Requirements are based on data from agricultural research stations and a well-established handbook (Agridea, 2011) for livestock growers.

Switzerland is fortunate in having excellent sources of data inputs for the inventory. The federal government regularly estimates crop production statistics at a national level. Food processing by-products are estimated from industry sources (milling, brewing) or by the government agricultural offices. Government production statistics are available for fodder maize and grassland forage production. Maize and grassland forage productivity from government statistics is corrected for altitude and meteorological conditions. Areal extents of seasonal grazing areas in the mountains are based upon infrequent (10–12 years) land-use mapping and GIS analyses.

Maize and grassland forage utilization is estimated to enable comparisons with forage availability. The two are presumed to be in balance over a multi-year period, with some having excesses and some having deficits. A forage deficit is covered by imports, or by drawing down standing stocks that have accumulated in years of excess. Utilization is based on typical dry matter intake rates of each livestock class and the duration of grazing.

3.2 INDIA

The Indian feed inventory

Several assessments have been carried out at regional level. Assessments have been based on land use data, crop production data and livestock census data (Anandan *et al.,* 2005;

Raju *et al.,* 2002). These data were obtained from the government Directorate of Economics and Statistics, and the Animal Husbandry Department. These researchers built on their experience to develop a database system with a user-friendly interface for accessing feed availability and requirements for the entire country (Angadi *et al.,* 2005).

An approach taken to assess national livestock feed supplies in India is described in Chapter 9. In this approach, crop-based feed availability is estimated from crop production data and green fodder availability is estimated from land classification data. Crop production and land utilization data (which include fodder land use types) are published annually. *Harvest indices* (the ratio of tonnes of utilizable crop by-product to tonnes of primary crop harvested) and *extraction ratios* (the fraction of primary crop harvested utilized for livestock feed) are applied to the crop production data to estimate feed availabilities. Harvest indices are used for crop residues and oil cakes, while extraction ratios are used for grains and bran/husks. Relatively crude estimates of green fodder production in various land types are used, along with estimates of percentages of land areas utilized for fodder production. These are approximations of mean values based on best available data. The production estimates are then applied to total land use areas, derived from land use maps and inventories.

Livestock feed requirements are estimated from livestock census data, which are published every five years. Livestock census data, broken down by species and age class, are converted to standard adult cattle units based on differences in body size. A basic estimate of dry matter requirements of 2 percent of body weight per day is then applied. Total dry matter requirements are compared with total feed availabilities to determine national feed balance.

Dikshit and Birthal (2010) calculated feed demand in India by scaling up from household level data. They argued that household level surveys are the only way to obtain reliable data on actual feed consumption. Scaling up was enabled by a sampling design that was intended to be as representative as possible across the wide range of heterogeneity of soils, topography, rainfall, irrigation, temperature, crops and livestock. The country was divided into 20 agro-ecological zones with further classification into 60 subzones based on variables such as soils, topography, rainfall, irrigation, temperature and crops. Furthermore, livestock were categorized by species, breed, age class and production status. Feed demands for each class of animal could then be combined with the distribution among classes to arrive at a more accurate estimate of aggregate demands. The scaling up was a multi-stage procedure, from households to villages, then from villages to districts, districts to regions, and regions to the nation. This accounted for the heterogeneity of villages in a district, and so on. These authors also compared feed demands with availability. They pointed out that the Ministry of Agriculture uses a general assumption that 5 percent of food grains are used for feed. They cited other literature with crop specific extraction rates (i.e. the fraction of total crop production utilized for feed), for example 9.5 percent of rice production and 41 percent of coarse cereal production. They projected future demands for feed in 2020 by first using "base year" feed consumption rates derived from their data, coupled with projected growth of livestock populations by types. They then revised the estimates to account for projected changes in demands for milk and meat. Based upon previous work, they predicted that future demands in milk would be met by increase in production per animal as well as numbers, while increased meat demands would be met primarily by increased animal numbers. However, irrespective of whether it is production per animal or numbers of animals, the energy requirements should remain the same unless feed conversion efficiency is somehow increased.

Mixed crop-livestock systems are very prevalent in much of the country, and there is great variety in the make-up and functioning of these households (Erenstein and Thorpe, 2010). The use of crops, crop by-products, forage, crop residues and other non-conventional feeds also varies markedly. It would be useful to understand this heterogeneity to more accurately assess livestock feed requirements. In the Indo-Gangetic Plains, uses of various types of livestock feed sources vary along an intensification gradient (Erenstein and Thorpe, 2010; Thorpe *et al.,* 2007), as determined by detailed village level surveys. Communities were randomly selected in a stratified cluster approach. Stratification was first applied to four sub-regions, then at the second level, three representative districts were selected, one from each of three main agro-ecological sub-zones. At the third level, six villages were randomly selected around a central point. This stratified approach is key to obtaining a representative sample, and for understanding how livelihoods and associated livestock feeding patterns vary in these systems.

3.3 PAKISTAN
The Pakistani feed inventory

The approach used in Pakistan is very similar to that used in India. In 2003, detailed calculations were carried out of feed availability and feed balance in different regions of the North West Frontier Province (now called Khyber Pakhtunkhwa) (Habib *et al*., 2003). Recently, a country level feed balance was carried out, including assessments in other provinces (Habib, 2010). Using crop conversion factors (like the harvest indices and extraction ratios used in India) found in the literature, and local data on crop productivities, quantities of crop residues and by-products derived from different crops were calculated approximately. Data on conversion factors for calculating crop by-product biomass need to be further developed and standardized.

Similarly, herbage from various categories of grazing lands was estimated using locally reported values for production and areas of grazing lands in ten different agro-ecological zones. However, the reported herbage yields from grazing lands in different ecological zones require updating and refinement, particularly because rangelands have degraded over the last 2–3 decades.

3.4 CHINA:
Present and projected livestock feed availabilities

Simpson, Cheng, and Miyazaki (1994) carried out a comprehensive assessment of agriculture in China in which they calculated present and projected livestock feedstuff availabilities. The calculations began with data from grain and oilseed crop production (total tonnes) and sown areas (hectares) from the China Agriculture Yearbook. Productivity per unit land area was calculated by dividing total production by sown area. Grains included wheat, rice, coarse (maize, sorghum etc.), while oilseeds included groundnut, rapeseed, sunflower and sesame. Other crop production statistics were also available including, for example, potatoes and sugar beets, and tree crops such as fruits. Cultivated and sown areas were reported by region and province. Production by the processed feed industry was described, including the roles of by-products and non-conventional feed sources. The China government does not publish statistics on the amount of grain fed to livestock. However, the authors utilized data from the U.S. Department of Agriculture on grain used for animal feeds in China.

China has a long history of utilizing non-conventional feed resources (NCFRs), crop residues and by-product feeds. NCFRs include a wide variety of substances including, for example, rice straw, azolla, cassava, banana rejects and maize stover. Examples of by-products include bagasse, brewers' grains, palm kernel cake, rice bran and poultry litter. As noted earlier, livestock in the Chinese dairy sector derived substantial fractions of their energy and protein-based feeds from crop residues and by-products, in systems where crops and livestock are tightly interlinked through transfers of biomass, energy and nutrients.

A feedstuffs availability model was developed and programmed as a spreadsheet. The model is based on the metabolizable energy and crude protein content of each crop, as well as grassland. The crop yield data are multiplied by sown areas to give total production, which is then multiplied by physical extraction rates – i.e. the proportions of each crop species comprised of grain, straw, brewers' grains, oilseed meal, etc. (for example, kg barley straw per kg grain) – to provide numbers of total quantities potentially available for both human and livestock utilization. Multiplication of the amount potentially available by the portion utilized by animals gives the total amount of feedstuffs that can be consumed by animals. The portions utilized were apparently estimated on the basis of expert knowledge. The proportions of oilseed meals utilized by animals are the products of subtracting estimates of losses due to transport and storage, animal refusal, waste, and use for fertilizer. A total of 38 crops, as well as four non-crop feedstuff sources (such as fishmeal), were considered. Each crop was partitioned into a primary output and any by-products or NCFRs. Grassland parameters included energy and protein contents, the extraction rate and area in hectares for five grassland types; warm, temperate, dry, arid and alpine. The inputted data from the approximately 1 000 parameters were then combined to calculate total energy and protein availability for livestock. Projections into the future were based on estimated growth rates in yield per hectare and sown areas.

Using this methodology, Simpson (2006) calculated that about 1.2 trillion Mcal of feedstuffs were produced in 2000. About 9 percent was derived from by-products, 13 percent from grasslands and 42 percent from grain crops. Non-conventional feedstuffs comprised 36 percent of all feed energy in 2000. About 800 million tonnes of residues and silage were calculated to have been produced in 2000, with residues accounting for 85 percent of that. The methodology was also used to assess China's beef production potential (Simpson, 2003) as well as consequences of potential changes in land use and agricultural productivities (Simpson, 2010b).

Long (2011) recently compiled and presented a number of statistics based on data from the Chinese Statistical Yearbook and other sources. These data show large increases in livestock-based food production and consumption. Per capita consumption of poultry and dairy both increased approximately 2.5-fold in the last 20 years. Red meat consumption increased from 21 kg/person in 1990 to 48 kg/person in 2009. Meanwhile, there was a significant decrease in food grain consumption. Small stock numbers increased 30–50 percent and dairy cattle numbers increased fourfold in the last 20 years. As a result of increased feed demands, China moved from being a maize exporter to an importer between 2000 and 2010. Annual soybean imports have risen from near zero to 50 million tonnes annually. Another consequence has been widespread rangeland degradation caused by overgrazing.

3.5 AFRICA

Use of crop residues in mixed crop-livestock systems

Crop residues (CRs) are roughages that become available livestock feeds after crops have been harvested. They are distinct from agricultural by-products (such as brans, oil cakes, etc.), which are generated when crops are processed (de Leeuw, 1997). A general consensus exists that there is enormous potential for better utilization of crop residues as livestock feed (Maehl, 1997). Crop residues are important in many national agricultural sectors, yet they are much underutilized at present. Ruminant livestock utilization of crop residues also contributes to the recycling of nutrients, and to soil fertility and structure, particularly in integrated farming systems. Cereal straws and stovers are by far the most important residues. National estimated residue yields were derived based on FAO production statistics for the production of food commodities (e.g. FAO, 1984, 1994), multiplied by factors as proposed by Kossila (1988). These multipliers can be replaced with more accurate estimates where possible.

Two kinds of ratios can be used to link grain and CR yield (de Leeuw, 1997). The first is a simple one in which grain yield is divided by an agreed factor expressing the harvest index, or proportion of grain to total above-ground biomass (Kossila, 1988). A second ratio is needed in relation to "edibility". To estimate the consumable fraction of a CR, data are required on parameters such as the likely removal rates by grazing animals or the refusal rates of stall-fed livestock.

Potential supplies of CRs in Africa (de Leeuw, 1997) can be approximated from country statistics on the proportion of land cultivated (e.g. World Bank, 1989; WRI, 1990), combined with yield estimates for the grains and tubers of the major crops (World Bank, 1989). These estimates are approximations and could be more accurate if better data for ratios of grain to CR were available. In Africa, restrictions on livestock access for CRs have become more common in recent years due to land privatization and intensification, so it can no longer be assumed that all of the potential CRs can be included in availability estimates.

3.6 SAHELO-SAHARAN REGION

Pastoral surveillance system and feed inventory in the Sahel

A Pastoral Early Warning System was developed by ACF (Action Contre la Faim) to monitor feed availability for pastoral livestock in the Sahelo-Saharan Region of Africa (Chapter 10). The system uses near real-time satellite imagery (vegetation greenness), ground data and livestock movement maps. Software has been developed to ingest and process these data to produce maps of feed availability in relationship to feed demands. A Normalized Difference Vegetation Index (NDVI) from SPOT 5 satellites is composited by VITO (Flemish Technologic Research Institute) over ten days at a 1 km x 1 km spatial resolution. VITO also produces a satellite-based Dry Matter Productivity (DMP) data product that is used.

A GIS overlay approach integrates the satellite-based vegetation data with additional spatial data characterizing accessibility of the forage to pastoralists and their livestock. A key constraint on availability is water, which may or may not be available within proximity to forage resources. Distance-to-water maps are used to determine which forage resources are sufficiently close to water to be utilized. Water availability maps are derived by combining remotely-sensed surface water maps with borehole maps. Water availability changes seasonally due to fluctuations in surface water. Availability is also constrained by unsuitable topography, particularly steep slopes.

Livestock distribution maps are then used to determine the distribution of feed demands. A simple feed balance is computed as the difference between feed availability and demand. In this way, areas of feed deficits can be readily identified, as well as areas of feed surplus.

The system is continually updated. At the end of each rainy season, a full feed inventory assessment is produced and made available to end users. ACF International intends to further develop the system and distribute it to countries in West and then East Africa.

3.7 SOUTHERN AFRICA

Development and application of Earth observation-based rangeland monitoring techniques in Namibia

The sparse network of rain gauges in parts of Southern Africa precludes a rainfall-based monitoring approach for forage biomass. Monitoring must, instead, be entirely based upon satellite data. A near real-time, satellite-based vegetation monitoring system called LARST (Local Application of Remote Sensing Technology) has been developed over the last decade (Chapter 11). The system is based on low cost satellite receivers that can download data from NOAA AVHRR (National Oceanic and Atmospheric Administration, Advanced Very High Resolution Radiometer) satellites. An antenna and receiver are set up locally and connected to a personal computer with the appropriate hardware and software. A methodology using a Vegetation Productivity Indicator (VPI) derived from such satellite data has been commissioned by governmental ministries in Namibia. The VPI is reported on a 10-day basis during the rainy season in map format and at the ministerial and agricultural district levels. The outputs are disseminated through workshop and training seminars and regular agro-meteorology bulletins produced by the Ministry of Agriculture.

A methodology has also been developed for combining satellite imagery (NDVI) with field observations of biomass for deriving near real-time maps of biomass estimates. Herbaceous biomass data are rapidly collected using a simple instrument called the disk pasture meter (DPM). Woody green leaf biomass is estimated using regression relationships with plant size, and by sampling plant size class distributions. Biomass is sampled along 1 km transects bisecting 1 km^2 sample sites. DPM readings are taken on both sides of the transect. The field biomass data are then regressed against the NDVI. The regression equations are then applied to NDVI maps to derive biomass maps.

3.8 MONGOLIA

Gobi Forage Livestock Early Warning System

A technologically advanced remote-sensing, GIS and simulation modelling system called the Livestock Early Warning System (LEWS) was applied to the Gobi pastoral region in Mongolia (Chapter 12). The LEWS combines field data collection from a series of monitoring sites, simulation model outputs, statistical forecasting and GIS to produce regional maps of current and forecast forage conditions. The system uses the PHYGROW[1] simulation model as the primary tool for estimating forage conditions. Field data, collected from monitoring sites established across the region, are used to parameterize and calibrate the model. Model runs for the monitoring sites are driven by near real-time climate data. The simulation model runs for each monitoring site are executed every 15 days and the outputs are made available via web portal (http://glews.tamu.edu/mongolia). To produce maps of forage conditions, the total forage available to livestock is output for each monitoring site and is co-located with remote-sensing imagery data (NDVI) data for the region and geostatistical interpolation is conducted to create regional maps of available forage. The LEWS system also incorporates a statistical forecasting system which provides a projection of available forage conditions for 60 days into the future (Chapter 12).

Climate data obtained from the Climate Prediction Center of the National Oceanic and Atmospheric Administration (NOAA) are used as driving variables for a forage simulation model. The model predicts forage biomass for monitoring sites throughout the region on a daily basis, along with soil water balance and livestock grazing offtake. Permanent vegetation transects have been established throughout the region to obtain information needed to parameterize the model. A geostatistical mapping procedure, specifically co-kriging[2], is used to develop regional forage biomass maps, with model output being the primary variable, and remotely-sensed vegetation greenness being the secondary variable. To forecast probable future forage conditions, an auto-regressive integrated moving average (ARIMA) forecasting model is used, providing a 90-day forecast of forage conditions. Training is provided to herders, NGOs and other stakeholders in the use of the LEWS. The LEWS forage inventory is continuously updated through the use of current climate and remote-sensing data, as well as ground-based monitoring data. The system is to be adopted and institutionalized at the Mongolian Agency for Meteorology, Hydrology and Environmental Monitoring.

3.9 CHINA
Remote sensing and *in-situ* observation-based livestock feed inventory on the Tibetan Plateau

A model/remote sensing-based approach has also been taken to assess feed resources for pastoralists on the Tibetan Plateau (Chapter 13). Two models are used, one to calculate total vegetation productivity, and the other to calculate standing forage biomass.

The vegetation productivity model uses the Enhanced Vegetation Index (EVI) derived from the MODIS satellite. The data are downloaded from the U.S. Geological Survey (USGS) data centre. The spatial resolution is 500 m x 500 m and the temporal resolution is eight days. The VPM also uses remotely-sensed photosynthetically active radiation (PAR) from the TOMS (Total Ozone Mapping Spectrometer) satellite, and temperature data from the China Meteorological Data Sharing Centre. The model assumes that vegetation productivity is

---

[1] PHYGROW is a point-based, daily time step, algorithmic or computation engine that models above-ground plant growth, forage consumption and hydrological processes.

[2] Kriging provides a means of interpolating values for points not physically sampled using knowledge about the underlying spatial relationships in a data set to do so. Cokriging is an interpolation technique that allows one to better estimate map values by kriging if the distribution of a secondary variate sampled more intensely than the primary variate is known.

fundamentally limited by intercepted PAR. The EVI is assumed to be directly related to the fraction of PAR that is absorbed by the vegetation. The maximum light (PAR) use efficiency of the vegetation is a parameter. Light use efficiency is also affected by temperature, water and plant phenological status. CO_2 gas flux measurements are used to parameterize and validate the VPM.

The forage biomass model uses the EVI to calculate aboveground biomass (AGB). The relationship between EVI and AGB is determined empirically. Forage biomass is taken as some fraction of AGB, with the fraction being dependent upon grassland type, utilization (grazing) period, type of utilization and grassland degradation status.

3.10 UNITED STATES

National-scale rangeland resource assessments

By law, the U.S. Secretary of Agriculture is required to prepare an assessment of the renewable resources of forest, range and other associated lands every ten years (Joyce, 1989). As part of that mandate, comprehensive assessments of the U.S. forage situation have been carried out (Joyce, 1989; Mitchell, 2000). The assessments were comprehensive and broad, covering the entire gamut of ecological, agricultural, economic and socioeconomic aspects of the situation. With respect to assessing forage supply, a main focus of both assessments was on land areas that were available to grazers and rangeland health. In the 1989 assessment, it was stated that the national production of forage is difficult to quantify, and that forage production is a function of the available land, productivity and land management. The implementation of range technology has not been nationally inventoried, however. A forage production model was used in which previous estimates by the Soil Conservation Service (SCS) for range site class productivities were employed. These took into consideration range condition and proper use factors to estimate appropriate stocking rates in terms of animal unit months (AUMs). A different approach was used for forested areas. Hay production estimates from the U.S. Department of Agriculture (USDA) were used. On public grazing lands, the amount of land permitted for grazing and associated stocking rates were set by individual management units.

Importantly, grazing is one of many uses that must be considered. Grazing is balanced with needs for wildlife, biodiversity, ecosystem services and recreation. Sustainable land and natural resource stewardship is paramount. Rangeland health is "connected to the broader concepts of sustainability and sustainable management" (Mitchell, 2000). "The Montreal Process is one standard for evaluating rangeland sustainability at a national scale through seven criteria: biodiversity, productive capacity, ecosystem health, soil and water conservation, contribution to the global carbon cycle, multiple socio-economic benefits, and a legal-institutional-economic framework."

Given these considerations, it was possible to sum up the total AUMs permitted on public lands in the United States; total AUMs stocked on private lands could be calculated from national statistics. Based on these sources, it was calculated that, nationally, 86 percent of beef cattle feed came from non-irrigated private land, 7 percent from public land, 5 percent from crop residues and 2 percent from irrigated pastures. However, it was also concluded that national forage assessments are difficult because forage production is simply not inventoried (Joyce, 1989). The lack of ecological knowledge regarding factors determining forage production was acknowledged and it was recommended that there is need for a more comprehensive understanding of plant growth and its responses to environmental factors.

3.11 GLOBAL
Assessment using IMPACT (International Model for Policy Analysis of Agricultural Commodities and Trade) and SLAM (Spatial Livestock Allocation Model)

A recent global-scale assessment of agriculture integrated three different models to assess the global human food situation and consequences for the environment (McIntyre *et al.,* 2009). They used IMPACT (International Model for Policy Analysis of Agricultural Commodities and Trade) (Rosegrant *et al.,* 2002), a partial equilibrium sector model, to provide insights into long-term changes in food demand and supply at regional levels taking into account changes in trade patterns. The IMAGE 2.4 model (Eickhout *et al.,* 2006) was used to carry out environmental assessments. Terrestrial changes simulated by IMAGE were then used as input to the GLOBIO-3[3] terrestrial biodiversity model (Alkemade *et al.,* 2006)

Specifically relevant here, they used SLAM (Spatial Livestock Allocation Model) (Thornton *et al.,* 2002; 2003; 2006) driven by livestock supply and demand outputs from IMPACT. The main role of SLAM was to convert livestock outputs of IMPACT (number of animals slaughtered) into livestock equivalents by livestock system in order to estimate grazing intensities, which would then be used as input into IMAGE 2.4. Four classes of livestock systems were recognized: landless, livestock only/rangeland-based, mixed rain-fed and mixed irrigated. Livestock were allocated to the four systems based on agro-climatology, land cover and human population density (Kruska *et al.* 2003). Grassland-based systems were further broken down into climate zones (arid-semi-arid, humid-sub-humid, tropical highlands/temperate). The Global Land Cover (GLC) 2000 data layer (JRC, 2005) was used, along with the GRUMP (Global Rural-Urban Mapping Project) human population data set at 1 km resolution (GRUMP, 2005).

IMPACT was also used by Delgado *et al.* (1999) to assess world grain production relative to increased demands by livestock. They parameterized the model with crop areas, yield growth trends, herd size and productivity, and initial levels and trends in feed conversion. Parameters were drawn from econometric analyses, expert judgments and a synthesis of relevant literature. Herrero *et al.* (2009) used IMPACT to predict crop and livestock production, prices, water use, income and malnutrition. A second step of their assessment used GIS to reallocate country and food production unit level outputs from IMPACT to different livestock production systems within countries and regions.

A major effort to assess global ruminant production systems was also model-based (Bouwman *et al*., 2005). The IMAGE modelling framework (Alcamo *et al*., 1998) was used as a starting point. Modelled livestock production for 1970-1995 was based on FAOSTAT data on production, use and trade of meat, milk, eggs and other products by animal category. Other FAO animal production data sources were also used (Bruinsma, 2003; Sere &

[3] GLOBIO is a modelling framework to calculate the impact of a number of environmental drivers on land biodiversity for past, present and future.

Steinfeld, 1996). Livestock feed requirements were derived from an existing energy balance model (EPA, 1994). Land cover maps used in IMAGE were used to estimate distributions of grassland and arable lands.

3.12 GLOBAL
Assessment of global human appropriation of net primary production (HANPP)

Much can be learned from efforts to assess how much of the annual biomass production by plants (net primary production, or NPP) is utilized by humans because a significant component of such assessments is the utilization of plant biomass for livestock feed. While these global-scale assessments may be relatively coarse to be of much use at a national level, global assessment methodologies are becoming increasingly fine-scaled, and are providing added details to spatial distributions of feed supply and use within countries.

The first attempt to carry out such an assessment (Vitousek *et al.,* 1986) did not attempt to calculate how much NPP is available for livestock feed, but it did calculate the amount that was probably used by livestock, as well as the fraction of total NPP used for feed. These authors used early estimates of global NPP that had been made by ecologists without the aid of modern GIS and remote-sensing databases. In their "low" estimate, which only included direct utilization, they relied on previous literature estimates of global livestock feed utilization (Wheeler *et al.,* 1981; Pimental *et al.,* 1980). In an "intermediate" estimate, they also included the amount of land converted to pasture for grazing, derived grazing lands (which accounted for 19 percent of total grazing land NPP), as well as anthropogenic fire losses. In their "high" estimate, they also included land lost to desertification. The rationale behind the intermediate and high estimates was that livestock require more plant material from the Earth's ecosystems than that simply counted as feed.

With the advent of GIS and remote sensing-based databases and models, it became possible to estimate the spatial distribution of NPP and its utilization over the Earth's surface (Imhoff *et al.,* 2004) more precisely. This analysis showed the uneven nature of human offtake, and the increasing importance of the movements of NPP products via imports and exports. This was useful for identifying areas of high impact (hotspots of sorts), areas of surpluses and deficits of demand compared with NPP, and thus implied "directions of net energy flow" spatially. From this, they could derive a "spatially explicit balance sheet of NPP supply and demand".

Imhoff *et al.* based much of their human food demands on FAO data, then used national level ratio of food demand to human population in combination with a human population map to create maps of demand. They used estimates of NPP from a global carbon model driven by remote-sensing data (Potter *et al.,* 1993; Slayback *et al.,* 2003). A review of other modelling assessments of global NPP can be found in Cramer *et al.* (1999). They estimated the amount of organic matter used as feed by applying efficiency values for grain (an average of 2.3:1 kg grain/kg carcass for all meat types) and for pasture (21.46:1 for ruminants) using data from previous studies. The total NPP required for grain feed was then calculated in the same way as for vegetal foods, adding residue and loss factors appropriate to each country's development status. It is worth noting that this approach is basically the same as calculating a feed balance and mapping it spatially, as is being done in some of the feed balance efforts reviewed in the case studies here (e.g. Chapters 10, 15).

The most recent assessment of HANPP was based on the best available global databases integrated in a high resolution GIS, used in combination with estimates of potential NPP from a dynamic global vegetation model called LPJ (Harberl *et al.,* 2007a, b). FAO statistical data (FAOSTAT) on livestock, agricultural yields and wood harvest at the country level were matched to a global land use map derived from a variety of GIS data sources. FAO livestock statistics were used to derive a feed balance for each country to calculate the biomass grazed that is not reported in the statistics. The NPP of the actual vegetation, including crops, was calculated by using LPJ to spatially allocate total NPP reported in the agricultural statistics. Cropland NPP was defined as the sum of harvested NPP, as reported in statistics and other fractions not accounted for in agricultural statistics. NPP of grazing land was calculated on the basis of LPJ runs that were modified to consider the effects of ecosystem and soil degradation, irrigation and fertilization. NPP utilized by grazing animals is not reported in agricultural statistics, so livestock feed balances were estimated on the basis of data on livestock numbers and livestock production from agricultural statistics (e.g. Wirsenius, 2003). Grazed biomass (offtake) was spatially allocated to grazing lands assuming it would be highest in the best-suited grazing areas and lowest in the least suitable ones.

In an assessment of the impacts of livestock on the global carbon cycle, Asner and Archer (2010) considered livestock feed utilization as just one of many of the impacts. They used satellite and modelling studies which estimated global NPP (Field *et al.,* 1998; Imhoff *et al.,* 2004) and determined the amounts of carbon fixed via primary production into crops and grazing lands (Sabine *et al.,* 2004), as well as the amounts of carbon actually consumed by livestock (0.45 Pg C/year), versus the total NPP including waste, seed production, allocation to roots and other ancillary flows (2 Pg C/year).

SECTION II

Methodologies and guidelines

4. A synthesis of methodologies available for national feed assessments

4.1 CALCULATING GROWTH IN LIVESTOCK FEED REQUIREMENTS

Although the primary focus of this document is assessment systems for national feed supplies, the need for such feed assessment systems is fundamentally driven by the question of whether feed supplies can meet future feed demands. The implications of feed availability for food security depend upon a corresponding assessment of feed demands.

An approach for calculating present and future demands for human food consumption is described in Chapter 7. Total projected food demand is calculated by multiplying projected per capita consumption rates by projected human population growth. Demands for animal source foods are included in this projection, based on current and predicted future dietary composition patterns. Using projected demands for animal source foods, the demands for animal feeds are calculated by employing feed conversion ratios.

The demands for livestock products are spatially distributed and mapped using maps of human population distributions. Consumption is mapped using the spatial distributions of rural and urban populations from the Global Rural Urban Mapping Project (GRUMP) and total human population numbers from projections made by FAO and other international organizations.

The diversion of crop production to livestock feeds is also a component of the human food requirement. Projected crop production requirements can be calculated by projecting future demands for livestock feeds. Crop products available to humans are calculated by subtracting crops used for feed, seed, waste and industrial production.

4.2 FEED SUPPLIES FROM CROP-BASED SYSTEMS

The approaches that have been developed to assess livestock feeds in crop-based or mixed crop-livestock systems are heavily reliant on crop production statistics that are developed by national government agencies. This is true in the highly developed system in Switzerland as well as the more recently developed system in India. Crop productivity data may take the form of biomass of crop and associated crop residues per unit land area. These data are then combined with land use data that characterize the amounts of land cover with different crop types.

A key aspect of this approach is the system that is utilized for categorizing land use/land cover and crop types. At some point, land cover mapping is required, in which land use/cover types are delineated spatially. The classes may be by crop species and/or cropping systems or more aggregated classes may be utilized. For improved accuracy, cover types would recognize variations in soils and climate that affect productivity. Alternatively, cover types could be overlaid with soil fertility and climate maps, such as precipitation and length of growing season, to develop a classification that accurately distinguishes crop types and differences in potential productivity due to environmental limitations.

The second primary data input is crop productivity. It is beyond the scope of this Manual to describe the various methods that are employed to estimate crop production. As noted, the feed inventories most often obtain crop production data from government agencies, so that aspect lies outside the feed assessment system. Undoubtedly, the data are ultimately based on an abundance of agricultural research and data obtained from commodity markets within the country. An important consideration, however, is the matching of crop production data to crop/land use/land cover data. A common classification system must be developed, or a system for converting between the classification system used for crop production data and the system used for crop/land use/cover data, in order to perform the calculations of total production for each of the crop/land-use/land-cover types.

Although a case study that employs remote sensing to estimate crop productivity is not presented here, there is a potential for doing so. Remote-sensing data are used as inputs to models of global primary production, as described above in the "Global-scale modelling" section. Remotely-sensed greenness or green biomass indices, integrated over time, can be used as a correlate of primary production along with the use of ancillary data such as crop-specific light use efficiencies, solar radiation and soil water availability.

Calculation of livestock feed availability from crop production data inevitably entails the use of factors which convert between total biomass production and actual feed biomass. In India, for example, an extraction ratio is used: the ratio of feed to total crop harvested (Chapter 9). In an assessment for China, extraction rates such as the proportions of crop comprised of grain, straw, etc. were used (Simpson *et al.,* 1994). The amount actually utilizable by animals must also consider wastage, losses in transport and storage, and fertilizer use. The basis for estimating these conversion factors is somewhat of a concern, because little documentation is provided for their sources. It is apparent that in many cases estimates are based upon little data and are rough approximations. Further research could be targeted to improving the data upon which such extraction ratios are based.

Conversion factors are also employed in calculating crop residues and by-products that are increasingly utilized for feed. In India, a conversion factor is used: the ratio of tonnes of utilizable by-product to tonnes of crop harvested (Chapter 9). The assessment for China (Simpson, 2006) included a partitioning of total crop production into the primary product as well as any by-products that could be utilized as feed. The section above on "Crop residues in mixed crop-livestock systems in Africa" employs factors that have been developed through more detailed studies (Kosilla, 1998). As with the extraction ratios, the sources of these conversion factors are not very apparent, and there is considerable room for the development of sound data sources. Considering the increased reliance on crop residues and by-products particularly in the developing world and in heavily populated regions, and the projected increased use of these sources, these data will become increasingly important.

Although few details have been provided here on the flows of feeds into and out of countries through imports and exports, these must be taken into account in national level feed balances. The Swiss system explicitly considers trade flows in its annual national feed balance assessment. It also considers changes in standing stocks, or reserves, all of which are necessary for predicting future capacity to cope with feed deficits, as necessary. Presumably, import and export data are the purview of entities concerned with commodity trading and market activities.

Another source of livestock feeds is by-products from food processing industries. In the Swiss example (Chapter 8), industrial food processing by-products that can be utilized for feed are estimated from industrial sources or agricultural offices. It is likely that this approach would be useful in many, if not most, countries where this is an important feed source.

The usability of crop-based and industrially produced feedstuffs by livestock is additionally affected by economics, which is in turn affected by the use of these feedstuffs for alternative, competing uses. For example, the use of molasses by livestock may be prohibitively expensive due to the high prices that humans are willing to pay to utilize molasses for food. Biofuels could become another significant competing demand for feedstuffs, which would also drive prices higher. Thus, merely accounting for "available" feeds will not work; their actual and potential uses will have to be considered. Price data will be key to availability for livestock. Assessments should relate feed prices and their nutritive values to the expected livestock products and their market prices (e.g. rice bran and pig live weight; sorghum and wheat straws; and rural and peri-urban milk prices).

4.3 FEED SUPPLIES IN SPATIALLY EXTENSIVE SYSTEMS

For spatially extensive livestock systems, remote-sensing data are indispensable. However, key ground data on forage biomass are also necessary for converting remote-sensing data to forage biomass amounts. The extensive nature of these systems also requires the use of a variety of spatially explicit data, GIS processing and modelling capabilities, as outlined in Chapter 16 on "Technologies, Tools and Methodologies for Forage Evaluation in Rangelands". In this chapter, four examples are given of systems that have been developed in which remote-sensing data, along with ground-based forage sampling data, are used to assess forage situations in pastoral regions. Two of these were developed as early warning systems to alert governments, aid agencies and pastoralists to developing situations of food shortages caused by drought or severe winter weather. A system was developed for the Sahel that ingests remote-sensing data on green biomass and water, along with additional GIS data (Chapter 10). A livestock early warning system (LEWS) was developed and has been employed in Africa as well as Asia (Chapter 12). A powerful feature of the LEWS is that it employs vegetation simulation modelling, driven by statistically projected precipitation data to estimate future risks of feed shortages. Remote-sensing data can also be used as inputs to relatively simple models of primary production, in combination with data on light use efficiency, solar radiation and temperature (Chapter 13). Yet another system employs locally installed receiving stations for downloading remote-sensing data (Chapter 11). The data are then processed, in combination with ground data on forage biomass, to develop forage biomass maps.

When extensive ground-based survey data are available, it is possible to carry out national level forage assessments without the aid of remote-sensing data. An approach for assessing forage resources at the national level in the United States relied on course estimates made by the U.S. Soil Conservation Service (SCS) of typical forage production values for range site classes contained in soil surveys (Joyce, 1989). These surveys were carried out over many years through the federally-funded activities of the SCS.

4.4 TECHNOLOGIES, TOOLS AND METHODOLOGIES FOR FORAGE EVALUATION IN GRASSLANDS AND RANGELANDS

Rangelands consist of grasslands, shrublands, savannahs and woodlands, and provide a significant fraction of the world's livestock feed resources (75 percent), particularly in regions with arid or semi-arid climates, and in developing countries. However, rangelands are often spatially expansive, heterogeneous, undeveloped in terms of accessibility, and low in human population presence. Unlike crops which are harvested and sold in markets in measured quantities, rangeland production is often imprecisely estimated, if at all. Production varies temporally with climatic conditions so mean values, if they are available, are often imprecise. Fundamentally, it is economically infeasible to invest sufficient resources in ground-based monitoring to provide the necessary data for national rangeland feed assessments. It has therefore proved especially difficult to develop national level feed inventories for rangelands.

Over the last three decades, there have been a host of technological developments in GIS, remote sensing and computer modelling of rangeland productivity that could be systematically applied to assessments of rangeland livestock feed situations over broad spatial scales. These technologies can be closely coupled with field-based sampling approaches that also have benefitted from recent technological advances such as GIS-based sampling protocols and near-infrared reflectance spectroscopy (NIRS) analysis of forage quality. An overview of these technologies is provided in Chapter 16.

Two suggestions are given for increasing the capacity to scale up a limited number of field-based forage biomass estimates to large areas. One is the use of field estimation techniques such as double sampling, which considerably reduces sampling effort and time. If done properly, aided by statistics, accuracy is little compromised. The second suggestion is to employ GIS and remote sensing-based spatial data to more effectively stratify sampling. Adequate sampling of each stratum permits the accurate scaling up for each stratum, and in aggregate, to a landscape or region.

Forage quality is as important as forage quantity in rangelands, because it is very often limiting and temporally variable. Without an estimate of forage quality, it is impossible to know what fraction of total plant biomass actually constitutes "feed". Indeed, while there may appear to be an excess of plant biomass, it may not all be consumable and, in the case of ruminants, material of low quality can reduce passage and forage intake rates. Direct estimation of forage quality over large areas and sufficient frequencies is prohibitive. However, NIRS has been shown capable of processing a large number of samples in a cost effective manner. For a national feed inventory, NIRS may be the most practical approach for assessing forage quality.

As shown in case studies for the Sahel, Tibet, Mongolia and southern Africa, remote sensing has proved to be indispensable for monitoring and assessment of the livestock forage situation over large areas. Chapter 16 provides an overview of the use of remote-sensing data for this purpose. In particular, remotely-sensed vegetation indices such as the NDVI have now been highly developed and widely applied. The data are commonly used as a direct correlate of green biomass and productivity or as an input to models which calculate productivity from the amount of radiation intercepted by green leaf biomass.

Though more demanding in terms of technological sophistication and expertise, dynamic simulation modelling of rangeland vegetation productivities, animals and ecosystem dynamics has advanced considerably over the last three decades. The models generally require a considerable amount of data but, once parameterized and tested, their capabilities extend well beyond purely empirical approaches. One unique feature is the capability to represent seasonal and inter-annual temporal dynamics in forage quality and quantity, and the potential effects of these variations on energy and nutrient consumption by livestock. Temporal variations can be more significant than mean or total annual quantities of forage production because periods of scarcity may ultimately prove to be what determines numbers of livestock that can be sustained.

Secondly, models can be implemented spatially, based upon GIS and remote-sensing data inputs, to consider the consequences of heterogeneity in topography, soils, vegetation and water availability. Such heterogeneity is extremely significant to mobile large herbivores (Coughenour, 2008). Often, resources are concentrated in key areas of the landscape, particularly during periods of scarcity. Third, the models are usually based on a mechanistic understanding of the processes involved in plant growth and animal production, as well as the ways that these processes respond to environmental variables. Fourth, the models are integrative, linking together climate, soils, vegetation and animals. They not only consider linear causes and effects, they also often consider feedbacks, for example of animals on plants and soils. Fifth, since they are driven by climate data, they have prognostic capability, that is, they can be used to make projections based on the current status of soil moisture, green biomass and likely scenarios of upcoming climatic conditions. Such models can also be used to examine outcomes of "what if" scenarios of climate, policy, livestock and human population increases, land use changes, and so on.

The effects of spatial distributions of topography, water and vegetation cover on livestock forage availability can be considered using GIS-based approaches. Although remote-sensing data can appraise vegetation biomass over large areas, not all of this biomass may be available due to unsuitable topography or long distances to water. Feed assessments must consider these limitations. Chapter 16 suggests possible approaches to this problem. Similar approaches were taken in the case study for the Sahel (Chapter 10). It is also possible to consider effects of topography and water on livestock spatial distributions in an ecosystem modelling approach (e.g. the SAVANNA model) (Chapter 15).

Potential stocking rates can be calculated by combining estimates of available forage with forage requirements per animal, the fraction of forage that can be consumed without causing degradation, and amounts required by wildlife and lost to fire. Actual stocking rates may be higher as a result of feed importation. Animal requirements can be calculated in considerable detail using nutritional balancing tools or models such as NUTBAL[4], which determine energy and protein requirements for maintenance and production. This is essen-

[4] NUTBAL is a software application whose primary purpose is to provide the livestock industry with the means to monitor the nutrient concentration in an animal's diet and determine if the current diet is sufficient to meet performance goals set by the producer.

tially the same approach as is utilized in calculating feed balances. The fraction of forage that can be sustainably consumed, also known as an allowable, or proper use factor, is highly significant, yet given little attention. It may vary widely, depending on plant species, soil fertility and the mode of grazing. The amounts that should be allocated to wildlife utilization, biodiversity or sustainable ecosystem service provision must also be carefully determined and factored into the feed availability assessment.

A computerized data management and quality control system will be necessary for a successful national feed assessment programme. Field data from across the country would have to be fed in, organized and made readily retrievable. Considerable amounts of data are involved in GIS, remote sensing and modelling technologies needed to cover large, diverse regions. While these technologies will be invaluable for rangeland feed assessments as described above, they would also be invaluable for crop-based feed and mixed crop-livestock systems, inasmuch as the productivities of these vary spatially and are intrinsically linked to land use and land cover. Feed assessment models, whether they simply consist of a series of calculations or are more elaborate dynamic simulations, involve organized data inputs and outputs, as well as pre- and post-processing.

4.5 FEED BALANCES FROM NATIONAL FEED ASSESSMENTS

While assessments of feed inventories and feed productive capacities provide critical information, the sufficiency of the feed supply can only be gauged relative to the demands for feeds. Essentially, this comparison between livestock requirements and feed supplies constitutes the feed balance. The feed balance can be calculated in terms of energy or specific nutrients or the amount of feed that would need to be imported to meet a country's feed requirements. Chapter 14 examines the basic methodologies involved in determining a feed balance. The steps taken in calculating a feed balance are: 1) estimation of feed supply, accounting for seasonality of supply, and feed losses due to inefficiencies, wastage, pests and disease; 2) quantification of animal numbers and production traits, in terms of live weight gains, milk production, egg production, and so on; 3) estimation of animal feed requirements, in terms of energy and nutrients, based upon animal species, age class, reproductive status and body mass; and 4) estimation of energy supplied from available feeds, accounting for factors affecting feed intake such as breed, age and feed accessibility.

In Switzerland, livestock census data obtained from government census units are combined with animal energy and protein requirements, which are based on research. In India, a similar approach is utilized, and it is recognized that livestock populations must be broken down by age, sex and functional classes as well as species, because requirements vary accordingly. Nutritional requirements may be quite simply expressed, for example, in terms of kg of feed per kg of body weight per day, or they may be more detailed, based on accurate estimates of energy and protein requirements for different breeds, body weights and animal functional types (Chapter 14).

Methods for assessing feed demands on a large scale are derived by scaling from data collected at local level. The multi-scale sampling approach described by Dikshit and Birthal (2010) is an example of a systematically designed sampling scheme that enables scaling up from households to villages, to districts and ultimately to the nation. Another approach is a stratified cluster design for village level surveys (Erenstein and Thorpe, 2010). These approaches highlight the importance of obtaining detailed data on the ground in order to characterize the wide range of variability and complexity across livestock production systems.

In spatially extensive systems, it is useful to develop feed balance maps, as was done in the Sahel (Chapter 10). Such maps identify locations where feed is in short supply or in excess, which can be responded to with livestock movements. Livestock distribution maps are developed based on information on the locations of pastoralists and their livestock. These are used to compute and map forage requirements. The requirements map is then compared with a map of feed availability to derive a map of feed surplus or deficits, which is useful knowledge for development planning and food relief efforts.

On larger scales (regional through global), maps of livestock distributions can be similarly used to assess the spatial distribution of livestock feed requirements in relationship to demands. Essentially, this would be equivalent to calculating and mapping the feed balance. The section below on databases provides examples of recent global livestock mapping efforts, although the uses of such maps to assess feed balances have been limited.

At a higher level, there is also concern for the human food balance, particularly the degree to which animal-source foods are able to meet human demands. The methodology employed in such assessments invariably involves the use of human population mapping, combined with per capita animal source food requirements (Chapter 7).

4.6 DATABASE SYSTEMS AND NATIONAL FEED ASSESSMENTS

National feed assessments will inevitably involve the collection and management of large amounts of data. Database systems are therefore an important component of the methodologies. The details of such systems cannot be provided here. However the reviews of existing feed assessment systems all point to database implementations of some sort. In highly developed systems, there is a centralized government database managed by a government agricultural statistics unit, as in Switzerland. Statistics are made available via reports and the internet. Accessible, user-friendly livestock feed data systems can also be developed, as has occurred in India. Clearly, the advents of spatial databases and GIS have made livestock feed assessments easier to carry out, and it has made the assessments more accurate. In crop-based systems, assessments are built on spatial data pertaining to crop/land use/land cover. In spatially extensive systems, the assessments almost entirely depend upon capabilities to process remote-sensing and GIS data, and in some cases, the capability to feed these data into forage production models, which are also spatially explicit. Examples of integrated data flow systems are provided in the descriptions of systems developed for the Sahel (Chapter 10) and Mongolia (Chapter 12). Further discussions of data processing capabilities are provided in Chapter 16.

While the aim here is to develop guidelines for national level feed assessments, awareness of FAO databases is potentially useful, in that there is a connection between FAO and country level databases. Given that FAO obtains its data from individual countries, it is true that the countries and not FAO are the ultimate data sources. However, FAO organizes the data in a particular way and makes it readily available. Increasing the accuracy of country level data on livestock feed availability and demands would consequently improve FAO's databases. As seen above, global scale estimates of human appropriation of NPP, as well as impacts of livestock on carbon balances, are ultimately tied back to FAO and thus country level assessments.

Since 1950, FAO has been preparing a World Census of Agriculture (WCA) (FAO, 2010 - http://www.fao.org/economic/ess/ess-wca/en/). The 2000 Programme was the sixth in the series. Since 1950, the WCA has been helping countries to carry out their national agricultural census at least once every decade using standard international concepts, definitions and methodology. WCA 2010 provides countries with a flexible approach to the collection of agricultural data on a variety of subjects in an integrated manner. FAO encourages countries to develop their programme of census and surveys, keeping in view their priorities, practices and resource availability. The following websites describe relevant methodologies.

www.fao.org/economic/ess/ess-wca/wca-guidelines/en/

www.fao.org/docrep/009/a0135e/A0135E04.htm

www.fao.org/docrep/009/a0135e/A0135E05.htm#ch8.3

Member countries provide the reports of their agriculture censuses to the FAO Statistics Division, which then disseminates the data through its website. FAOSTAT (http://faostat.fao.org) provides time-series and cross sectional data related to food and agriculture for some 200 countries.

The national version of FAOSTAT, CountrySTAT (http://www.fao.org/economic/ess/ess-capacity/countrystathome/en/), is being developed and implemented in a number of target countries, primarily in sub-Saharan Africa. It will offer a two-way data exchange facility between countries and FAO, as well as a facility to store data at the national and sub-national levels. CountrySTAT gathers and harmonizes scattered institutional statistical information so that information tables become compatible with each other at the country level and with data at the international level. The main objectives are to facilitate decision-maker's access to information and to bind data sources that are currently spread throughout the different institutions.

The other half of the feed balance equation involves knowledge of livestock densities, in order to calculate feed demands. Global livestock distribution databases have also been developed with FAO support. These are useful for global assessments, but the methodologies that have been employed could also be applied at more detailed national level. The Animal Health and Production Division (AGA) of the FAO commissioned the development of a global Livestock Atlas over a decade ago (FAO, 2001). It was realized that livestock and animal production statistics vary considerably from country to country, meaning that regional or continental datasets are often incomplete. Consequently, methods were developed to fill in data gaps based on distributions across environments where statistics were available. Regression techniques were used to establish statistical relationships between known livestock numbers and various environmental parameters, including those derived from satellite imagery. Livestock and cropping data were derived from country level databases supplied to FAO. These data were supplemented by more detailed surveys and censuses, where available, and a variety of novel statistical techniques were used to determine animal numbers within different ecological zones in each country.

The use of spatial distribution models has been further developed since then (FAO, 2007). These models use predictor variables such as human population density maps, distances to roads and city lights, elevation and length of growing season. Remote-sensing data inputs include NDVI, air and land surface temperature, a rainfall surrogate, humidity and potential evapotranspiration. The models are used to try to fit observed cattle densities derived from national census reports, livestock surveys and data archives. While national livestock census data are inputs into the model, the value here is in the spatial allocation of livestock data at a finer level of resolution than administrative boundaries, and in relationship to spatial distributions of GIS and remote sensing-based predictor variables. Species of livestock are mapped individually, including cattle, buffaloes, sheep, goats, poultry, and pigs and their gridded global maps are freely available (http://www.fao.org/AG/againfo/resources/en/glw/home.html). In addition, livestock can be allocated among livestock production systems using the model of Thornton *et al.* (2002; 2003). This creates an opportunity to estimate feed requirements more precisely because livestock diets for livestock in different production systems are more precise than simple species level diets.

4.7 ENVIRONMENTAL CONSIDERATIONS IN NATIONAL FEED ASSESSMENT

It would be an oversimplification to assume that livestock feed inventories sufficiently characterize the demands placed on natural resources and ecosystem services by livestock production activities. It would be negligent to recommend guidelines for carrying out livestock feed assessments without also considering these associated demands. Indeed, a broader definition of "feed balance" would consider not just the requirements of livestock for nutrition, but also the requirements for sustainable ecosystem services. The multidimensional aspects of these requirements and desirable future courses of action were examined in a study coordinated by FAO, USAID and the World Bank (Haan, Steinfeld, and Blackburn, 1996).

The assessment of LEAD (Livestock, Environment and Development) (FAO, 2006b) noted the increased demand for livestock products globally and the effects that has had on the environment. The pressures include marked expansion of land used for grazing and the advent of grain feeding and consequent demands for feed grains and arable land. It found that two antagonist trends are at play: on the one hand, production growth will further increase land demand by the sector, though at diminishing growth rates. On the other, continuous intensification will reduce the area of land used per unit of output. The relative strength of these two trends will determine the trend in total area used by livestock. It was shown that large amounts of N fertilizer are used for maize and other animal feed, especially in nitrogen-deficit areas such as North America, Southeast Asia and Western Europe. More than half of total maize production is used as feed. Other feed crops are also important consumers of chemical N fertilizer. Releases of CO_2 and other greenhouse gases were also quantified.

The multiple effects of livestock in the context of global changes in human populations, land use and climate have been reviewed many authors (Steinfield *et al.,* 2010). Han *et al.* (2010) recognized that the livestock sector is the most important global land user, and competition for land, water, fossil fuels, and climate change will be main drivers of future livestock systems. The demand for feed grains will expand to meet the continuous growth in demand for meat and milk. Many systems have shifted from grassland-based to mixed farming, and above all, to intensive production in landless systems, especially pigs and poultry. Gerber *et al.* (2010) showed that livestock are a major user of land resources, for fodder and feed production. Meat and milk production are growing faster than pasture and cropped areas due to intensification. There is particularly strong intensification and clustering in pig, poultry and dairy sectors. Reid *et al.* (2010) examined effects on biodiversity. The bigger impacts of livestock on biodiversity appear to be indirect, through deforestation to create pastures, the growing feed trade, and pollution of waters and emissions of greenhouse gases. They identified two "syndromes" by which livestock affect biodiversity. The extensive dryland syndrome occurs on moister fringes of drylands, as rangelands contract to make way for cropping and settlement, with significant impacts on biodiversity. The simplified intensive syndrome occurs where grazing is heavy and wildlife are all but excluded, and only grazing tolerant plants are able to thrive.

Feed lies at the interface of the positive and negative effects of livestock, income, livelihoods and the environment (Asner and Archer, 2010). The most profound effect of livestock on the global carbon cycle is a growing set of worldwide ecological degradation syndromes including deforestation, woody encroachment and desertification. There is also a wide range of collateral carbon flows, including losses to the atmosphere via tropical deforestation.

Feed importation to cover deficits can lead to increased environmental pressures in the way of increased stocking rates, which consequently impose increased grazing pressures on pastures, grasslands and rangelands. Although the increased feed supply that arises from importation may seem to meet animal needs, stocking rates are often raised above levels to which they would be regulated due to feed deficiencies. For example, a system that is supplemented with feeds in winter may result in higher stocking and grazing pressures on grasslands during the growing season. A second consequence of feed importation is the increase in animal waste materials and associated nutrients which must be appropriately managed to prevent nutrient accumulations in the environment, on land, in water, and through gaseous emissions (e.g. nitrous oxides). These responses may occur as a result of intra- as well as inter-national scale feed redistributions.

Blümmel *et al.* (2010) identified additional issues. One hundred times more water is needed for livestock than is used by livestock for drinking, due to use in feed production. Over 90 percent of water used in livestock agriculture is for producing feeds (FAO, 2006b). The use of rough crop by-products reduces digestive efficiency, leading to increased methane (a greenhouse gas) production. The use of roughage for feeds competes with uses for soil improvement and the leaving of crop residues in place as a part of zero tillage can be important for conservation agriculture.

Livestock can also have beneficial effects on their environments. In many areas, such as in many of the developing countries of Africa and Asia, livestock convert crop residues to manure which is then used to enrich soil fertility without the use of chemical fertilizers. A secondary benefit of crop residue use is a decreased use of grains for animal feeding. Herbivores can promote vegetation productivity under certain conditions (Frank *et al.*, 1998; McNaughton, 2001). Properly managed grazing regimes can also increase water infiltration rates and provide improved microsites for seed germination (Savory, 1988).

To summarize, livestock feed production is tied to ecosystem functioning, ecosystem services and ecological sustainability. What is produced now may or may not be sustainable, in environmental terms. What can be sustainably produced in the future, similarly, cannot be determined without consideration of environmental responses. Trade-offs with values arising from alternative land uses, such as wildlife habitat preservation, biodiversity conservation and ecosystem service provision must also be taken into consideration.

5. Guidelines for the development of National Feed Assessment Systems (NFASs) and the implementation of National Feed Assessments (NFAs)

5.1 OVERVIEW

The process of implementing a National Feed Assessment System (NFAS) occurs in three phases: 1) planning, 2) establishment and 3) updating. In the ***planning*** phase, procedures and designs are developed for the implementation of the assessment system. The ***establishment*** phase implements a fully operational system based on these procedures and designs. During the ***updating*** phase, the NFAS is sustained and improved as technology and user needs and expectations evolve. Here, the three phases of developing and maintaining a NFAS are described. The procedures are not meant to be strictly adhered to in all situations. Instead, they are suggested procedures, and they should be adapted to best fit the situation and conditions in each country or region that develops a NFAS.

The target audiences of the guidelines are members of national and regional governments and of research organizations who wish to establish a NFAS. The aim here is to provide guidance not only on technical issues but on the procedural aspects of building and institutionalizing a NFAS. It may be noted that proper understanding of the analysis and synthesis presented in the proceeding sections is a prerequisite for proper implementation of the approaches and procedures outlined here. Familiarity with the technical issues, especially related to methodologies for assessment of extensive feed resources (Chapter 16), would be helpful background information. The case studies given in Chapters 7–15 will serve as examples and aid in the establishment and updating of a NFAS. The guidelines were developed in discussions with a wide variety of subject matter experts in various aspects of feed production, livestock feed requirements and livestock production systems. Their expertise included experience in assessing livestock feed availabilities across a wide range of environments, from spatially extensive, low production systems based primarily on natural grasslands, to spatially intensive, high production, mixed crop-livestock systems.

5.2 PLANNING PHASE

5.2.1 Objectives

1. Develop a preliminary understanding of national feed resources within the context of evolving livestock systems

Before a NFAS can be developed, it is critical to develop an understanding of the feed resources in the country in question, because the NFAS will be designed to address the types of feed resources that exist there. Furthermore, the NFAS will be targeted to the types of livestock production systems that occur there. These systems will have specific needs for feed resources, and they will be based on established modes of feed acquisition and delivery. Given that livestock production systems are continuously evolving, anticipated trends in livestock systems must be anticipated in order for the NFAS to be useful into the future.

2. Plan and develop an agreed set of procedures for carrying out national feed and feed balance inventories for all types, gradations and mixtures of grassland/rangeland-based and crop-based systems

Various methodologies, approaches and analytical tools for assessing feed availability in rangeland and crop-based livestock systems are described in Chapters 7–16 of this document. These tools are available, and they can be applied to various livestock systems as appropriate. However, the process of establishing a NFAS involves more than tool selection; for example, knowledge of institutional and organizational aspects is also important.

5.2.2 Stepwise process

1. Form a task force or working group

The first step is to establish a planning and design task force. The composition of the task force should include people with a wide variety of relevant subject matter expertise regarding livestock production systems in a broad range of environments and settings, as well as people with expertise on the procedural and organizational aspects of implementing national-scale database systems. Technical expertise will be needed in various aspects of livestock and feed production systems, agricultural statistics and spatial databases. The task force might also include stakeholders who are affected by various aspects of livestock feed production activities and feed availabilities. These could include livestock producers, government ministries, private sector representatives, NGOs and researchers or domain experts. The stakeholder group may be particularly important in rangeland and pastoral systems where feed resources are shared.

1.1 Identify and recruit task force or working group members

Key members might include:

- People with skills and knowledge in agricultural resource statistics and agricultural systems analysis;
- People with extensive knowledge of rangeland and crop-based livestock production systems, and animal nutrition;
- People with technical capabilities in GIS, remote sensing, database design, statistics, sampling and surveys;

- People with multi-disciplinary expertise, that is, with broad, large-picture, integrative, systems-level perspectives. These persons would be accustomed to working on multi-disciplinary problems in coordinated teams. For spatially extensive rangeland systems, this includes people with an understanding of pastoral systems (breeding, ecology, herd and pasture management, pasture yield measurements, disease and socio-ecology). For crop-based systems, this includes people with expertise in crop production, mixed crop-livestock systems and intensive livestock production systems;
- People from farmers' or livestock keepers' associations, and pastoral NGOs;
- People from government ministries overseeing agriculture, land use and the environment;
- People from the private sector who are involved in feed production;
- People from NGOs and research institutions who have relevant experience; and
- Proponents, including individuals who are in a position to push the implementation forward with respect to government institutions and other potential end user groups.

1.2 Identify desired outputs of the NFAS (needs assessment)

The task force should carry out an initial needs assessment to identify the types of systems and livestock feed data that already exist, and the feed data that do not exist but which are needed by decision-makers. It may be necessary to retain consultants and outside experts to participate in this assessment. A primary objective here is to identify what information will be useful to decision-makers. What are the questions that the data will provide answers to? What are the objectives of the NFAS? The assessment should consider how the information will be complied, managed, used and updated. Specific outputs should be identified and assessed in terms of information content, the utility of the data and the potential costs of producing the data. The feasibility of producing the desired data outputs could be assessed in a preliminary manner.

Desired outputs from the NFAS may include static databases, or a dynamic assessment process, or a system that has the ability to forecast future feed situations. The outputs should be identified in terms of the following:

- Format and mode of delivery (maps, documents, web sites, data bases); and
- Specific output variables to be reported; for example:
  - total feed biomass, available feed biomass, accessible feed biomass;
  - feed balance situations, number of animals that can be fed given available or accessible supplies;
  - animal products that can be produced with the available feed (milk, meat, other products);
  - anomalies in feed biomass availability, or deviations from normal;
  - seasonal, annual temporal variability and dynamics of feed availabilities;
  - projected feed availabilities into the future; and
  - uncertainty measures and statistical confidence levels.

1.3 Initial design for the inventory system

The design of the inventory system will involve processes of agreeing on terminology, approaches, methods and tools. This could occur through meetings, planning workshops, and internally and externally reviewed manuscripts. The feed resource components that will be considered must be explicitly identified. Terminologies for feed resource categories and production processes that are in currently in use are often not widely understood, precisely defined or agreed upon. The range of approaches, methods and tools is wide, and not all approaches can be expected to be suitable for the feed situations at hand. Data availabilities will vary among regions and countries. Between rangeland and crop-based systems there is a particularly wide divergence in terms of the approaches used and the types of data that are required and available. The range of approaches is demonstrated in the case studies presented in this document (Chapters 7–15). It can furthermore be expected that situations will arise in which existing approaches must be modified or expanded upon. Finally, data sources, data flows and analytic processing must all be attached to personnel who are in appropriate positions, and who have appropriate expertise. These personnel should be identified and their roles clearly stated and understood. In essence, the design of a NFAS is about systems design, in the truest sense. A system is a set of interacting components and processes. In this case they are interlinked through data flows. The processes and flows are mediated by specific personnel.

The steps to be taken in the design process include the following.

- Define the target feed and livestock systems, their typology and terminology
  - review available typologies and terminologies;
  - select and refine the typology as appropriate;
  - develop an initial glossary of terminology.
- Develop an initial design for the inventory system
  - identify overall data flows and data base designs, decision flows and specify algorithm capabilities;
  - identify existing methods, tools, algorithms, models, and data processing streams for use, and develop new methods and procedures as necessary;
  - identify participants and their roles (data sources, data users, analysts, institutional linkages, partnerships).

2. Define key classification parameters, develop a classification system, and observe commonalities among classes

The purpose of developing a livestock production system classification is to establish a framework for calculating livestock feed availabilities according to class of production system. It will improve the accuracy of the national assessment if the within-nation systems are disaggregated in such a way as to enable calculations for functionally similar types of production systems. If functionally dissimilar systems are aggregated, the feed calculations will most likely be less accurate.

2.1 Identify the key parameters that will capture the essence of various livestock production systems

The classification system will be based upon key parameters. The key parameters must be chosen with the aim of capturing key functional differences among livestock production systems. For example, functional groups of livestock production systems may be based on types of livestock, types of feed, biophysical characteristics, geographic locations and degree of integration with trade at local through international scales. It will be expedient to identify the minimum set of parameters that will have to be assembled to achieve acceptable accuracy.

2.2 Develop the livestock production system classification

The challenge here will be an acceptable, yet useful, level of aggregation. A broad classification might begin with the distinction between spatially extensive rangeland, mixed crop-livestock, and industrial/landless systems. There will be issues of what constitutes an acceptable level of aggregation. For example, crop-livestock systems might be subdivided into rice/beef systems, wheat/dairy buffalo systems and rice/pork systems, if that subdivision is based on meaningful differences in livestock feed requirements and feed sources.

2.3 Develop an increased understanding of the differences and commonalities of various livestock production systems

Develop processes for stimulating thought that results in improved understanding of a country's (and region's) livestock production systems and their dynamics and, within that broad context, the key role of feeds. Key differences and commonalities among systems will become increasingly apparent as this systems analysis is refined over time. As a result, the classification system, and the NFAS which is built upon it, will also become increasingly accurate. This process of improving understanding can be accomplished through a variety of approaches, such as networking, workshops, educational activities, and internal and external reviews.

3. Identify the methods, tools, and resources required

3.1 Assess methods and tools required in terms of technological capabilities

The methods and tools that will be used in the NFAS will be based upon existing and available technologies. The NFAS should not be designed based upon technologies that cannot be accessed. Thus, the technology that is required must be assessed in relationship to the available technological capabilities. Technological capabilities will vary among countries, among regions within countries, and among institutions within countries. For example, it can be expected that some areas might have high capabilities to use satellite/GIS data, while others will be dependent on various conventional field methodologies, and others will integrate the two approaches to varying degrees. Likewise, computation and data processing capabilities will also vary.

3.2 Assess the resources required to produce and maintain the system

The NFAS must be designed in light of the resources that will be available to produce and maintain the system. Required resources will include expertise, infrastructure, organization, personnel time and funding. Each of these must be taken into consideration. While people in-country will have general knowledge of the expertise and infrastructure that is available, it will be useful to characterize and quantify these in some way because this is related to the resource requirements. The amount of personnel time that will be required and that is available will depend on multiple factors. If the work is to be carried out within an existing institution or government unit, for example, existing personnel time may need to be freed up, and the amount will be constrained by other organizational needs. Funding resource requirements must be quantified, and sources identified. What will it cost to develop and then maintain the NFAS? Where will the funding come from?

3.3 Formulate algorithms and describe models in a preliminary or draft fashion

The NFAS will involve modelling and computation, as raw data are processed and combined to produce meaningful outputs. The exact mathematical procedures for deriving a data product must be laid out, though not necessarily fully developed in this *planning phase*. Here, the models and algorithms can be presented in a preliminary or draft fashion, and they can be more fully developed in the *establishment phase*. Models and algorithms could, for example, be presented as flow diagrams, with specific computational processes identified in terms of data inputs and derived outputs.

4. Identify data needs and sampling strategies

4.1 Identify data needs and potentially available data sources

The design of the NFAS will include specifications for data inputs and sources. Data inputs must be characterized in terms of what is being measured, how it is measured, how often it is measured and how accurate it is. At this stage, a preliminary assessment should be carried out of potential data sources and modes of delivery and access. This will likely include ground-based data on feed resources, remotely-sensed data on forage biomass, GIS data for a wide range of variables, crop production rates and harvest coefficients, and data on livestock production systems from household surveys.

4.2 Inventory current data sets, methods and tools, and conduct a needs assessment or gap analysis to identify missing data

Here, the actual work of inventorying data sets, methods and tools must be carried out in the context of a needs assessment. Inventories will likely need to assess multiple existing and potential sources for a variety of input data. The sources must be assessed in terms of ease, reliability and costs of accessing data. Similarly, existing methods and tools must be inventoried in terms of the certainty that they will be available or developed, how reliable they will be, and how costly they will be.

4.3 Develop a sampling strategy for household surveys to define a baseline

It is highly likely that many data inputs will be derived from household surveys and subsequently scaled up to villages, regions and, ultimately, the country. Consequently, a sampling scheme must be developed which includes sampling criteria for selecting representative systems within countries. The representative systems would be identified on the basis of the livestock production system classification noted above. Household surveys would provide data on livestock types and numbers, their feed types and sources, and their economics. The sampling strategy should be well designed statistically, so that case study results can be extrapolated to the larger, overall production system type.

4.4 Identify necessary resource and logistic inputs required for the data collection and sampling programmes

Data collection and sampling programmes will have been identified as above, however the resource and logistic inputs for these programmes must also be explicitly identified. Given that large areas are being covered at a national level, the need for resources could be quite significant and it is likely that resources will constrain the intensity of sampling that can actually be achieved. As such, once the resources are identified, it is likely that the sampling scheme will have to be revisited given these constraints. This is especially likely to be the case in in spatially extensive rangeland systems because large land areas with little infrastructure must be covered. In these areas, remote-sensing data will have to be used to the greatest extent possible. Remote-sensing data will be useful in both rangeland and crop-based regions, so the resources required to obtain and process these data must be carefully identified.

4.5 Develop data processing flows

Data obtained from multiple sources will need to be processed through structured databases and computational procedures. Database design is central to the NFAS. Significant effort will be required to design the structure of the databases and computational processing for transforming primary input data into derived data that are useful for assessing livestock feed availabilities at a national level. Depending on the organization of the NFAS, data may be processed centrally, or in a distributed fashion, with data coming into multiple data processing nodes distributed throughout the country, processed, and then sent on to a central, national level data processing facility.

5. Conduct feasibility studies of alternative approaches

While the NFAS design will be designed as carefully as possible, it is not guaranteed that the design will prove to be feasible once put into practice. Until the NFAS procedures are actually put to the test, it will remain uncertain as to whether they will actually prove to be feasible. Implementation of the first pass design will likely reveal areas with unanticipated capability shortfalls. Thus, it might be prudent to carry out feasibility studies of various aspects of the NFAS, which may lead to revisions in the design. The feasibilities of alternative methods, tools and means of output delivery should be considered. Feasibility studies might also include analyses of the sensitivity of outputs to the uses of alternative approaches. This could help in securing funds for establishing and maintaining the NFAS, because such studies would provide evidence that particular areas of the NFAS require additional funding to ensure that the entire NFAS is capable of providing the desired outputs.

6. Develop strategic papers

The development of strategic or white papers is an important "intermediate" step. In particular, it would be useful to develop a high-impact article addressing focused issues and problems with the development and establishment of a NFAS. Such an article would bring attention to the utility and importance of a NFAS and would highlight the challenges for its implementation. This would be useful as a focal point for the team that is working on the NFAS, for the stakeholders who stand to derive benefits from the NFAS, and for all interested parties, including the press, who would convey the story to the public and to policy-makers who have influence on national funding decisions.

7. Develop functioning regional partnerships

7.1 Identify stakeholders and partners for implementation and institutionalization

The roles of stakeholders and partners are delegated in terms of the results that are desired, and the types of inputs they are able to provide.

Stakeholders and partners are central for the implementation of the NFAS because they will undoubtedly play a variety of important roles in its ongoing operation and utilization. They may, for example, be data providers, or they may be facilitators of data sources. They will also play a role in its institutionalization. The NFAS will become an important part of the nation's livestock production system. It will become something that producers and consumers both rely upon. As such, it must have a reliable home and a dependable support system.

7.2 Analyse stakeholders and partners in terms of their desired outcomes, potential conflicts, synergies, overlaps and domains of interest

The stakeholders and partners will have varied roles, contributions, capabilities and desired outcomes. In order for these entities to function synergistically, it will be necessary to analyse their characteristics. There may be synergies, overlaps or conflicts among their potential roles and desired outcomes. These must be resolved by delegating specific roles to each entity in order to minimize conflicts and maximize synergies. In effect, this is another example of a systems analysis, in which multiple entities interact to produce a whole that is more than the mere sum of the parts.

7.3 Establish linkages to potential key partners from local communities or districts

Partners at the local community and district level will be important as data sources as well as users. The task of establishing linkages to local and district partners will be a substantial project, and will need to be identified as such. The necessary monetary, logistic and human resources must be anticipated as part of a plan to accomplish this task.

7.4 Propose and formally agree upon the partnerships

The partnerships must be formalized and agreed to in order for them to be tangible, and in order for the partners to commit and have the responsibility to follow through. The agreements will lay out the roles and responsibilities of the partner, as well as the NFAS. The NFAS will also have responsibilities to the partners. The relevant authorities or leaders will need to sign, but it may be expected that these leaders will have to seek the support of their constituencies, particularly if significant resources are involved.

8. Acquire funding for the required infrastructure (computers, labs, etc.), staffing and personnel

Funding for infrastructure and personnel will be required to establish and run the NFAS. The acquisition of funding must occur in the *planning phase*.

9. Establish or utilize existing institutional frameworks

An institutional framework must be created. The institutional framework is the backbone of the NFAS as an organization. The details of the NFAS will be built on this framework. The NFAS institutional framework may be comprised of a single NFAS organization, or it may be comprised of a coalition of organizations with diverse roles and responsibilities. It may include regional collaborations given the trans-boundary nature of many of the spatially extensive livestock production systems.

10. Develop an initial interactive data portal and web service to disseminate information arising from the planning phase

The results of the *planning phase* should be communicated as effectively as possible. The results should be made available in the internet via a web page. Secondly, a prototype data portal and web-based data service should be developed and presented or beta tested at this stage. A web site that informs users and enables data access should be central to the NFAS. At the end of the *planning phase*, users should be accessing a prototype version, providing feedback on the planned capabilities and possibly testing some of its preliminary functions using test data sets in their anticipated formats.

5.3 ESTABLISHMENT PHASE

5.3.1 Objectives

1. Implement the designs developed during the planning phase to construct a fully operational feed inventory system providing information on a regular basis

This is the primary objective of the *establishment phase*. The goal is to implement the plans and establish the first version of the NFAS. It can be anticipated that issues will arise and will need to be resolved to improve upon the first version. A stepwise process is presented below for carrying out the implementation.

2. Create inventories of livestock feed resources and conduct assessments of feed balances at local through district levels

The first outputs from the NFAS will be produced at local through district levels. The first assessments will be conducted in a select, representative subset of locales. The outputs will be evaluated and made available for internal and external review.

3. Scale up the planned approaches, methods and tools to the national level

Once the NFAS has been tested and refined in a subset of representative locales, the NFAS can be implemented throughout the country. The first national scale assessment will, in effect, be a summation of assessments from all of the regions.

5.3.2 Inputs

Success in the *establishment phase* will depend on a number of inputs, most of which will have developed as outputs from the *planning phase*.

1. The plans and designs from the planning phase, including agreed upon terminology, approaches, methods and tools

Here, the plans and designs developed during the Planning Phase will be implemented for the first time. The plans should be followed as closely as possible, but it is also likely that modifications will occur as the implementation proceeds.

2. The funding that was secured in planning phase

The NFAS cannot be implemented without sufficient funding. The *planning phase* will have provided cost estimates for the implementation, and accordingly, funding sources should have been identified. These funding sources must now be activated.

3. The institutional framework that was established in the planning phase

The institutional framework must be in place, because it will be the basis for the partnerships and collaborations necessary to implement the NFAS. This should consist of functioning regional partnerships and an interactive data portal and web service. The interactive data portal and web service will facilitate communication, and information and data sharing.

4. A technical body or organization within the framework of existing institutions

A technical body or organization will oversee the overall operation of the NFAS. While this entity will be new, it will most likely exist with the framework of existing institutions such as government ministries, national laboratories, universities and the private sector, because they will already have in place the highest level of technical expertise that is available in the country. The technical body could be the same as the Task Force identified in step 1.2 of the *planning phase*, or it could be an outgrowth of the Task Force.

5. Existing capabilities and infrastructure as identified in the planning phase

The necessary capabilities and infrastructure will have been identified in the *planning phase*, but not necessarily developed. This applies to the local as well as national level. Existing facilities can be built upon or leveraged.

6. Existing data sources that were identified in the planning phase

Data sources that were identified as already existing must be shown to be in place and operational.

7. The tools and methodologies identified and preliminarily developed in the planning phase

During the *planning phase*, tools and methodologies will have been identified and developed in preliminary or prototypic forms.

5.3.2 Stepwise process

A stepwise process is suggested here to establish a NFAS. These steps are only intended to serve as guidelines for a logical sequence of actions leading to a functional NFAS. The importance, necessity and level of investment in the suggested steps will no doubt vary among countries and among regions within countries, depending on the needs and capabilities at hand.

1. Establish and train personnel

At the outset, staff must be put in place to carry out the establishment, including the actual development, of the NFAS. Shortly thereafter, staff must be put in place to process data coming from local and regional sources, from other existing institutions and from remote-sensing platforms. Staff must be put in place that are responsible for data flow from local to national levels where local data are processed and synthesized to form the national assessment. All of these personnel may require some degree of training.

2. Develop needed technical capabilities and infrastructure beyond what exists already (Input 5)

The development of these resources must occur at the beginning of the establishment phase. It would be cost and time effective to build on or leverage existing facilities. Data handling and computational facilities and capacities will be critical. Remote-sensing hardware and software may be required. Infrastructure is necessary for carrying out household surveys and feed resource sampling. Needed resources may involve transportation, laboratory space, office space and housing.

3. Develop detailed technical specifications that are fully developed and documented

These would include specifications for:

- data types to be collected;
- data collection procedures;
- quality control procedures;
- analysis and interpretation processes;
- data production processes;
- algorithms, data flow procedures;
- database systems - including metadata;
- reporting processes; and
- interpretation of the assessment system products, in terms of when and where they can "help", and their limitations.

The full development of technical specifications based on the designs produced in the *planning phase* may occur at the outset of the *establishment phase*. Although these specifications may have been developed in the later stages of the *planning phase*, this level of detailed design requires resources which may not be put in place until the *establishment phase*. These resources include personnel, infrastructure and funding. It will be important to document the specifications so that they are standardized and replicable. Formal documentation also provides a basis for analysis, discussion and precisely targeted improvement efforts.

4. Further development of data sources

If data sources do not exist (Input 6) or if existing data sources need to be modified to suit the needs of the NFAS, then the data sources must be developed. Of course, the entire

NFAS depends on data from a wide range of sources. Sources include field data, GIS data, remote-sensing data and data being obtained by other institutions such as District Offices, and Ministries of Agriculture or Trade. Consequently, institutional arrangements may be required for data access.

5. Develop tools and methodologies

These were identified and designed in the *planning phase* (Input 7). During the *establishment phase*, they must be fully developed and tested. The tools and methodologies will be developed for data processing, computation, GIS, remote sensing and field surveys, for example. The personnel involved in tool development will be equally diverse, and are likely to be distributed among multiple teams working on various aspects of the NFAS. Since data will flow among various units, and activities must be coordinated, it will be useful if not necessary to establish cross-unit working groups.

6. Carry out the first implementation of the system to conduct a national livestock feed assessment

The first implementation of the NFAS will be carried out, no doubt in experimental mode in which the procedures are tested, evaluated and refined. Given that feed resources are dynamic, varying seasonally and annually, the assessment should include estimates of feed resources tabulated and mapped in a time series starting with a recent base year. It will be important to test the ability of the system to capture the full range of variability. The system must be shown to incorporate and process necessary data during different conditions because feed resources vary in quantity and quality.

7. Deliver and disseminate the assessment products

Products should be disseminated to stakeholders, agencies, universities and any other interested end users. An interactive data portal and web service should be resourced and activated to make the data available to any and all. Advice should be provided on the proper use of the data.

8. Validate the assessment system outputs

A variety of tests could be devised to validate estimated feed availability. Estimates should be checked against independent data sets, that is, data sets that were not used as inputs. For example, feed estimated from land use and climate data could be compared with estimates derived from market or livestock production data. When outputs are derived from remote sensing or computed from ancillary input data (e.g. precipitation, land use), there should be a methodology in place for the verification of assessment outputs against ground truth data. Validation studies should be designed using a structured sampling framework to ensure representativeness across the full range of diversity in production systems.

9. Assess the assessment system

Conduct an analysis of system capabilities and deficiencies, including a needs assessment for required improvements. Evaluate whether the system is able to produce timely and accurate data, and data that are useful to end users. Is data coverage adequate? Is it representative? Can available resources be more optimally utilized and distributed? Evaluate the efficiencies and factors that reduce efficiencies of data assimilation, processing and reporting.

10. Institutionalize the assessment system and ensure there are mechanisms to maintain the necessary infrastructure for its continued application

This step includes:

- the identification of the national implementing partner;
- the establishment of an institutionalized coordinating team. The institutional structure could be at a national level. However, regional transboundary issues prevail in spatially extensive rangelands systems and will increasingly affect crop-based systems because of increasing market utilization by livestock producers;
- the establishment of a central government budget line to support the system, along with capabilities for the necessary mobilization of resources, capital and recurrent expenditures; and
- the establishment of a regional training programme for staff who will implement the system, as well as end users who will use the outputs of the system.

11. Train stakeholders in the proper use of the data outputs

The stakeholders must be trained in the proper use of the data. This must include understanding of the intended scope and power, and conversely, the limitations of the data. The developers and participants in the NFAS would of course have the greatest understanding. However, outside analysts and consultants could develop the necessary expertise to provide this training to others.

12. Develop mechanisms to promote sharing of knowledge and experience with other countries, via an international network, or through existing regional organizations

Sharing of experience, knowledge and ideas with other countries will provide opportunities for learning. The cross-fertilization of ideas will promote creative solutions to the benefit of all. An international network of NFASs would be one way of bringing this about. The network could have a common web site or forum for exchange of information and ideas. International network meetings could be held annually or biannually. Information sharing could also take place through existing regional organizations with established memberships, for example agricultural, livestock producer and other professional organizations, scientific societies, or NGOs concerned with various stakeholder interests.

5.4 UPDATING PHASE

5.4.1 Objectives

1. Develop a process for ensuring that the NFAS is maintained and employing state-of-the-art technology and providing outputs that are relevant to current demands

The NFAS will need to be maintained, improved and updated with ongoing technological advances. This will be as much, if not more, about institutional change as it is about technologies.

2. Identify who and with what resources the system will be maintained

For the NFAS to be stable and sustainable it must have a home and a system of caretakers and overseers. This will entail the establishment of ownership. It will also entail the development of a sustainable source of income, possibly from government sources, but quite possibly also from private sources, particularly end users.

3. Ensure that the system is providing up to date, quality-assured information at relevant time scales

The NFAS must be evaluated routinely to ensure that the data it is providing is timely and accurate. The timelier the information is, the more useful and powerful it will be for decision-making. Timeliness should be evaluated in relation to the important time scales of variations in feed availability. Significant fluctuations may occur on monthly, seasonal and inter-annual time scales. In addition to climate-driven rapid changes in growing conditions, attention should be given to slowly changing variations in underlying parameters, such as land use, changes in livestock feeding practices and even societal changes.

5.4.2 Stepwise process

1. Secure funding for ongoing monitoring, system maintenance and updating

The NFAS will require a funding source to run and maintain over the long term. The utility of the results of applying the system will need to be demonstrated to potential funding sources. This, in turn, will depend on user feedback as well as results of assessments of the NFAS. It will be important to show that there is an established user base and that the NFAS outputs in some way enhance livestock production and human well-being.

2. Report the validated approaches, methods, tools and agreed terminology

Users, developers and any interested parties should be able to learn about the NFAS in as much detail as they desire. The NFAS operations must be described in a transparent way, so that all parties can understand what it is, what it does, what it requires as inputs, and what it produces as outputs. Approaches, methods and tools should be described in both simple and technical terms. Technical terminology should be clearly defined; otherwise the documentation that uses these terms will be opaque to readers.

3. Develop a process for obtaining feedback from end users, funding agencies, outside experts

The feedback process will likely entail surveys, workshops and independent reviews. An external advisory panel and/or steering committee could be established to assimilate the results of the feedback process and make recommendations for system improvement.

4. Ensure that current, state-of-the-art knowledge and institutional structures are being employed in the inventory, both in the technology behind the data acquisition, and in the interpretation and analysis of the data

Assessment system personnel must be kept up to date with the current state of the science via training, participation in conferences and research. Internal reviews could be carried out. An external advisory panel or steering committee could be established to periodically evaluate the system in this regard.

5. Conduct biannual reviews of the system, identifying strengths and weaknesses, areas where the system could be improved, and where data gaps exist

Annual or biannual reviews should be conducted to ensure that the NFAS is up to date in all respects. External reviews by experts provide valuable fresh insights and knowledge. Reviews by end users and stakeholders provide feedback on system performance related to needs and expectations. Internal reviews are valuable in that system participants have in-depth knowledge of system shortfalls and data gaps. Reviews should be constructive rather than simply being critical.

6. Refine the terminology, approaches, methods and tools

These are the central tasks involved in updating the NFAS. Terminology will need to be refined as more is learned about the factors involved in livestock feed production and availability. The increased knowledge will lead to more precise definitions of terms. The approaches, methods and tools will be refined with knowledge gained through experience and with technological advances. Experience will lead to increased understanding of what works and what does not. New ideas will arise as the NFAS provides new insights into the country's livestock feeding systems. New sources of data can be expected to come on line. New computational capabilities will be developed.

7. Develop general relationships between key livestock system parameters and observed results from monitoring sites

Over time, data from the assessments can be analysed to try to find general relationships between key production system parameters and feed availabilities among sites. Key parameters may be biophysical, organizational or economic in nature. The purpose here is to develop an increased understanding of the primary factors governing feed availability. Indeed, these scientific analyses could be carried out and published for a wide audience. The increased understanding resulting from these analyses could be used to strengthen livestock feed production systems and increase the resilience of the livestock production sector as a whole.

8. Provide ongoing training and capacity-building

Knowledgeable and skilled personnel will be required to keep the system functional into the future. Expertise will be required with respect to knowledge of livestock production systems, as well as hardware, software, databases and administration. Funding must be in place to support this training. Linkages with universities could be beneficial in this regard, because knowledge could be gained from them, and knowledge of current approaches could also be transmitted to faculty and students.

9. Ensure that the system is adapting to changing needs within the country

End users may increase in number and diversity, or they may change. The system must respond to these changing needs through the development of new approaches. This could be accomplished through recurrent needs assessments. Above all, the NFAS will continue to exist only if it is meeting the needs of its users and stakeholders.

6. References for Sections I and II

Agridea. 2011. *Wirz Kalender 2011. A set with two handbooks*. ISBN 978-3-7245-1656-9.

Alcamo, J., Kreileman, E., Krol, M., Leemans, R., Bollen, J., Minnen, J.V., Schaeffer, M., Toet, S., de Vries, B. 1998. Global modelling of environmental change: an overview of IMAGE 2.1. *In* R. Alcamo, R. Leemans, E. Kreileman, eds. *Global Change Scenarios of the 21st Century. Results from the IMAGE 2.1 Model.* Elsevier, Oxford, pp. 3–94.

Alkemade, R., Bakkenes, M., Bobbink, R., Miles, L., Nelleman, C., Simons, H. & Tekelenburg, T. 2006. GLOBIO 3: Framework for the assessment of global terrestrial biodiversity. *In* A.F. Bouwman, T. Kram & K. Klein Goldewijk, eds. *Integrated modelling of global environmental change. An overview of IMAGE 2.4*. Netherlands Environment Assessment Agency (MNP), Bilthoven, The Netherlands.

Anandan, S., Raju, S.S., Angadi. U.B. & Ramachandra, K.S. 2005. Status of livestock and feed resources of Malnad Region in Karnataka. *Anim. Nutr. Feed Technol*., 5: 99–105.

Angadi, U.B., Raju, S.S., Anandan, S. & Ramachandra, K.S. 2005. Database on availability and requirements of animal feed resources in the country. *Indian J. Anim. Sci.,* 75: 1083–1086.

Asner, G.P. & Archer, S.R. 2010. Livestock and the global carbon cycle. Chapter 5 *In* H. Steinfield, H.A. Mooney, F. Schneider & L.E. Neville, eds. *Livestock in a changing landscape Vol. 1*. Island Press, Washington, D.C., USA.

Blümmel, M., Duncan, A., Poole, J., Gerard, B. & Valbuena, D.. 2010. Livestock: the good and the bad. *Proceedings 7th Biennial Animal Nutrition Association Conference - Animal Nutrition Strategies for Environmental Protection and Poverty Alleviation*. Odisha University of Agriculture and Technology, Bhubaneswar, Odisha, India, 17–19th December, 2010. pp. 16–20.

Bouwman, A.F., Van der Hoek, K.W., Eickhout, B. & Soenario, I. 2005. Exploring changes in world ruminant production systems. Agric. Systems 84:121–153.

Bruinsma, J.E. 2003. *World Agriculture: Towards 2015/2030. An FAO Perspective.* Earthscan Publications, London.

Coughenour, M.B. 2008. Causes and consequences of herbivore movement in landscape ecosystems. Chap. 3. *In* K. Galvin, R. Reid, R. Behnke & N.T. Hobbs, eds. *Fragmentation of semi-arid and Arid Landscapes: Consequences for Human and Natural Systems.* Springer. The Netherlands.

Cramer, W. 1999. Comparing global models of terrestrial primary productivity (NPP): overview and key results. *Glob. Change Bio.* 5 (Suppl. 1): 1-15.

de Leeuw, P.N. 1997. Crop residues in tropical Africa: trends in supply, demand and use. *In* C. Renard, ed., *Crop residues in sustainable mixed crop-livestock farming systems*. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) India. CAB International, Wallingford, UK.

Delgado, C., Rosegrant, M., Steinfeld, H., Ehui, S. & Courbois, C. 1999. *Livestock to 2020: The next food revolution*. International Food Policy Research Institute (IFPRI), Washington D.C., USA.

Devendra, C. 1982. Malaysian animal production in perspective. *Proc. VIth Ann. Conf. Malaysian Society of Animal Production*, pp. 201-219.

Devendra, C. 2009. Intensification of integrated oil palm – ruminant systems: enhancing productivity and sustainability in South East Asia. *Outlook Agric.,* 38: 71–81.

Devendra, C. & Leng, R.A. 2011. Feed resources for animals in Asia: issues, strategies for use, intensification and integration for increased productivity. *Asian-Aust. J. Anim. Sci*., 24: 303–321.

Dikshit, A.K. & Birthal, P.S. 2010. India's livestock feed demand: estimates and projections. Agric. Econ. Res. Rev. 23:15-28.

Eickhout, B., van Meijl,H. & Tabeau, A. 2006. Modelling agricultural trade and food production under different trade policies. *In* A.F. Bouwman, T. Kram & K. Klein Goldewijk, eds. *Integrated modelling of global environmental change. An overview of IMAGE 2.4*. Netherlands Environ. Assessment Agency (MNP), Bilthoven, The Netherlands.

Erenstein, O. & Thorpe, W. 2010. Crop-livestock interactions along agro-ecological gradients: a meso-level analysis in the Indo-Gangetic plains, *India. Environ. Dev. Sustain.* 12:669-689.

EPA. 1994. *International anthropogenic methane emissions: estimates for 1990.* EPA 230-R-93-010, US Environmental Protection Agency, Washington, DC.

FAO. 1984. *FAO production yearbook, Vol. 38*. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO. 1994. *FAO production yearbook, Vol. 48*. Food and Agriculture Organization of the United Nations, Rome, Italy.

FAO. 2001. *Livestock geography: An introductory atlas of animal resources*. FAO. Rome, Italy.

FAO. 2006a. *World agriculture: Towards 2030/2050: Interim report. Prospects for food, nutrition, agriculture and major commodity groups*. FAO, Rome, Italy.

FAO. 2006b. *Livestock's long shadow.* Livestock Environment and Development (LEAD), FAO. Rome, Italy.

FAO. 2007. *Gridded livestock of the world 2007*, G.R.W. Wint & T.P. Robinson. 131 pp. Rome, Italy.

FAO. 2010. *World census of agriculture 2000*. FAO statistical development series 12. FAO, Rome, Italy.

FAO. 2011. *World livestock 2011 – Livestock in food security*. Rome, FAO, Italy.

Field, C.B., Behrenfeld, M.J., Randerson, J.T. & Falkowski, P. 2004. Primary Production of the Biosphere: Integrating Terrestrial and Oceanic Components. *Science,* 305: 367–371.

Frank, D. A., McNaughton, S.J., & Tracy, B.F. 1998. Ecology of the earth's grazing ecosystems. *BioScience* 48: 513-522.

Gerber, P., Robinson, T., Wassenaar, T., & Steinfeld, H. 2010. Livestock in geographic transition. Chapter 4, *In* H. Steinfield, H.A. Mooney, F. Schneider & L.E. Neville, eds. *Livestock in a changing landscape Vol. 1*. Island Press, Washington, USA.

GRUMP. 2005. *Global urban-rural mapping project (GRUMP)*. Available at http://beta.sedac.ciesin.columbia.edu/gpw. Center for Int. Earth Science Inform. Network (CIESIN) of the Earth Inst., Columbia University, New York, USA.

Haan, C. De, Steinfeld, H. & Blackburn, H. 1996. *Livestock and the environment: Finding a balance. A Study coordinated by the Food and Agriculture Organization of the United Nations, the United States Agency for International Development and the World Bank*. WRENmedia, Suffolk, U.K. Available at www.fao.org/docrep/x5303e/x5303e00.htm.

Haan, C. De, Gerber, P. & Opio, C. 2010. Structural change in the livestock sector. Chapter 3 *In* H. Steinfield, H.A. Mooney, F. Schneider, L.E. Neville, eds. *Livestock in a changing landscape Vol. 1*. Island Press, Washington, USA.

Haberl, H., Erb, K.H., & Krausmann, F. 2007a. Human appropriation of net primary production (HANPP) – Entry prepared for the *Internet Encyclopaedia of Ecological Economics*. Available at http://www.ecoeco.org/publica/encyc.htm.

Habib, G. 2010. Best practices in animal feed production and management in SAARC countries. SAARC Agricultural Centre, Farmgate, Dhaka, Bangladesh.

Habib, G., Siddiqui, M.M. & Suhail, S. 2003. Livestock action plan: Livestock management, feeding, and health in Northwest Frontier Province, Pakistan. Report on FAO Project TCP/PAK/0168. NWFP Agricultural University, Peshawar, Pakistan.

Harberl, H., Erb, K.H. Krausmann, F., Gaube, V., Bondeau, A., Plutzar, C., Gingrich, S., Lucht, Q. & Fischer-Kowalski, M. 2007b. Quantifying and mapping the human appropriation of net primary production in earth's terrestrial ecosystems. *PNAS,* 1–4: 12942–12947.

Herrero, M., Thornton, P.K., Notenbaert, A., Msangi, S., Wood, S., Kruska, R., Dixon, J., Bossio, D., Steeg, J., van de Freeman, H.A., Xianglin, Li, Sere, C., McDermott, J., Peters & M., Rao, P.P. 2009*. Drivers of change in crop-livestock systems and their potential impacts on agro-ecosystems services and human well-being to 2030*. CGIAR systemwide livestock programme, ILRI, Nairobi, Kenya.

Herrero, M., Thornton, P.K., Notenbaert, S., Wood, A., Msangi, S., van de Freeman, H.A., Bossio, Dixon, J., Peters, M., van de Steeg, J., Lynam, J., Parthasarathy Rao, MacMillan, S., Gerar, B., McDermott, J., Sere, C. & Rosegrant, M. 2010. Smart investments in sustainable food production: revisiting mixed crop-livestock systems. *Science,* 327: 822–825.

Imhoff, M.L., Bounoua, L., Ricketts, T., Loucks, C., Harriss, R. & Lawrence, W.T. 2004. Global patterns in human consumption of net primary production. *Nature,* 429: 870–873.

Joyce, L. A. 1989. *An analysis of the range forage situation in the United States: 1989–2040*. General Technical Report RM-180. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 137 pp.

JRC (Joint Research Centre of the European Commission). 2003. *GLC 2000: Global Land Cover Mapping for the Year 2000*. European Commission Joint Research Centre, Institute for Environment and Sustainability. Ispra, Italy.

Katigile, J.A., Said, A.N. & Dzowela, B.H. 1987. Animal feed resources for small-scale livestoc producers: Proceedings of the second pasture network for Eastern and Southern Africa (PANESA) workshop. International Development Centre, Ottawa, Canada.

Kossila, V. 1988. The availability of crop residues, in developing countries in relation to livestock populations. *In* J.D. Reed, B.S. Capper, *&* P.J.H. Neate, eds. *Plant Breeding and the Nutritive Value of Crop Residues*. Proceedings of a Workshop, 7–10 December 1987, International Livestock Centre for Africa (ILCA), Addis Ababa, Ethiopia, pp. 29–39.

Kruska, R.L., Reid, R.S., Thornton, P.K., Henninger N. *&* Kristjanson, P.M. 2003. Mapping livestock-orientated agricultural production systems for the developing world. *Agric. Syst.* 77: 39–63.

Long, Ruijun. 2011. Role of herbivores in integrated agriculture in China. International Centre for Tibetan Plateau Ecosystem Management, Lanzhou University, China. Pers. Comm., paper presented in Aberystwyth, UK.

Maehl, J.H.H. 1997. The National Perspective: A Synthesis of Country Reports Presented at the Workshop. *In* C. Renard, ed*. Crop Residues in Sustainable Mixed Crop/Livestock Farming Systems*. International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) India. CAB International, Wallingford, UK.

McIntyre, B.D., Herren, H.R., Wakhungu, J., & Watson, R.T. 2009. *Agriculture at a Crossroads Global Report*. IAASTD International Assessment of Agricultural Knowledge, Science and Technology for Development. Island Press. Washington D.C., USA.

McNaughton, S. J. 2001. Herbivory and trophic interactions. *In* J. Roy., B. Saugier & H.A. Mooney, eds. *Terrestrial Global Productivity: Past, Present, Future.* Academic Press, San Diego, pp. 101-122.

Mitchell, J. E. 2000. *Rangeland resource trends in the United States: A technical document supporting the 2000* USDA Forest Service RPA Assessment. Gen. Tech. Rep. RMRS-GTR-68. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 84 pp., USA.

Mudgal, V. D. ***&*** **Pradhan, K.** 1988. Animal feed resources and current patterns of utilisation in India. *In* C. Devendra, ed. *Proceedings of non-conventional feed resources and fibrous crop residues in India*. International Development Research Centre, Ottawa, Canada. pp. 139–146.

Pica-Ciamarra, U., N. Morgan & D. Baker. 2012. Core livestock data and indicators" results of a stakeholder survey. A paper of the World Bank, FAO, ILRI Livestock Data Innivation in Africa Project, with support from the Gates Foundation (available at: http://www.fao.org/ag/againfo/home/documents/2012_PAP_Core_Livestock_Indicators_120503.pdf).

Pimental, D., P.A. Oltenacu, M.C. Nesheim, J. Krummel, M.S. Allen & S. Chick. 1980. The potential for grass-fed livestock: resource constraints. *Science,* 207: 843–848.

Potter, C. S., Randerson, J.T., Field, C.B., Matson, P.A., Vitousek, P.M., Mooney, J.A. & Klooster, S.A. 1993. Terrestrial ecosystem production: a process model based on global satellite and surface data. *Global Biogeochem. Cycles*, 7: 811–841.

Rae, A. & Nayaga, R. 2010. Trends in consumption, production, and trade in livestock and livestock products. Chapter 2 *In* H. Steinfield, H.A. Mooney, F. Schneider & L.E. Neville, eds. *Livestock in a changing landscape Vol. 1*. Island Press, Washington, USA.

Raghavan, G. V., Krishna, N. ***&*** **Reddy, M.R.** 1995. Priorities for feed resources use in the semi-arid Tropics. *In* C. Devendra *&* P. Gardiner, eds. *Global agenda for livestock research. Proc. of the Consultation for South Asia region,*. Patancheru, India, International Livestock Research Institute, Nairobi, Kenya, pp. 37–52.

Raju, S.S., Anandan, S., Angadi, U.B., Ananthram, K., Proasad, C.S. & Ramachandra, K.S. 2002. Assessment of animal feed resource availability in southern Karnatak Region. *Indian J. Anim. Sci.,* 72: 1137–1140.

Ramachandra, K. S., Raju, S.S., Anandan, S. & Angadi, U.B.. 2005. Animal feed resources and its impact on livestock production in India. *Indian Dairyman*, 57: 39–47.

Ramachandra, K.S., Taneja, V.K., Sampath, K.T., Anandan, S. ***&*** **Angadi, U.B.** 2007. *Livestock feed resources in different agro ecological zones of India: Availability, requirement and their management*. National Institute of Animal Nutrition and Physiology, Bangalore, India, 100 pp.

Reid, R. S., Bedelian, C., Said, M.Y., Kruska, R.L. Mauricio, R.L. Castel, V., lson, J. & Thornton, P.K. 2010. Global livestock impacts on biodiversity. Chapter 8 *In* H. Steinfield, H.A. Mooney, F. Schneider & L. E. Neville, eds. *Livestock in a changing landscape Vol. 1*. Island Press, Washington.

Rosegrant, M.W., Cai, X. & Cline, S.A. 2002. *World water and food to 2025: Dealing with scarcity*. IFPRI, Washington DC., USA.

Sabine, C.L., Heimann, M., Artaxo, P., Bakker, D.C.E., Chen C-T.A., Field, C.B., Gruber, N, Le Quere C,, Prinn, R.G., Richey, J.E., Romero, P., Sathaye, J.A. & Valentini, R. 2004. Current status of past trends of the global carbon cycle. Pp. 17–45 In: Field, C.B., Raupach, M.R.,eds. *The Global Carbon Cycle – Integrating Humans, Climate, and the Natural World. SCOPE 62, Island Press, Washington.*

Savory, A. 1988. *Holistic resource management.* Washington, DC, USA: Island Press. Pp. 545.

Sere´, C., Steinfeld, H. 1996. *World livestock production systems. Current status, issues and trends.* Animal Production and Health Paper 127, Food and Agriculture Organization of the United Nations, Rome.

Shrestha, H. R. & Pradhan, D.R. 1995. Research priorities for animal agriculture by agro-ecological zones in Nepal. *In C.* Devendra & P. Gardiner, eds. *Global agenda for livestock research,* Proceedings of the Consultation for South Asia region. Patancheru, India, International Livestock Research Institute, Nairobi, Kenya, pp. 85–102.

Simpson, J.R. 2003. China's long-term production potential evaluated. *Feedstuffs,* 75(40): 20–22.

Simpson, J.R. 2006. *China's dairy industry: Current situation and long-term projections.* Presented at WERA-101: Assessing China as a market and competitor 2006 Conference on China's evolving agricultural economy: Biotechnology, food markets and policy liberalization Washington, D.C. April 24–25, 2006.

Simpson, J.R. 2010a. Land Use, Production to Shape China's Future (Second segment of a three-part series*). Feedstuffs,* 82(41): 14–15.

Simpson, J.R. 2010b. Feedstuffs Play Key role in China's Food Needs (Third segment of a three-part series). *Feedstuffs*, 82(42): 16–17.

Simpson, J.R., Cheng, X. & Miyazaki, A. 1994. *China's Livestock and Related Agriculture: Projections to 2025*. CAB International, Wallingford, UK.

Slayback, D. A., Pinzon, J. E., Los, S. O. & Tucker, C. J. 2003. Northern hemisphere photosynthetic trends: 1982–99. *Global Change Biol.,* 9: 1–15.

Speedy, A.W. 2003. Global production and consumption of animal source foods. *J. Nutr.,* 133: 4048S–4053S.

Steinfield, H., Mooney, H.A., Schneider, F. & Neville, L.E.. 2010. *Livestock in a changing landscape Vol. 1*. Island Press, Washington D.C., USA.

Steinfeld, H., Wassenaar, T. & Jutzi, S. 2006. Livestock production systems in developing countries: status, drivers, trends. *Rev. Sci. Tech. Off. Int. Epiz.,* 25: 505–516.

Thorpe, W., Erenstein, O., Singh, J., & Varma, A. 2007. Crop-livestock interactions and livelihoods in the Gangetic plains of Bihar, India. Research report 12. ILRI, Nairobi, Kenya.

Thornton, P.K., Jones, P.G., Owiyo, T., Kruska, R.L., Herrero, M., Kristjanson, P., Notenbaert, A., Bekele, N. & Omolo, A., with contributions from Orindi, V., Otiende, B., Ochieng, A., Bhadwal, S., Anantram, K., Nair, S., Kumar, V. & Kulkar, U. 2006. *Mapping climate vulnerability and poverty in Africa*. Report to the Department for International Development, ILRI, PO Box 30709, Nairobi 00100, Kenya. Pp 171. [Online] Available at http://www.dfid.gov.uk/research/mapping-climate.pdf. ILRI, Nairobi.

Thornton, P. K., Kruska, R.L. Henninger, N., Kristjanson, P.M. & Reid, R.S.. 2003. Livestock and poverty maps for research and development targeting in the developing world. *Land Use Policy,* 20: 311–322.

Thornton, P.K., Kruska, R.L., Henninger, N., Kristjanson, P.M., Reid, R.S., Atieno, F., Odero, A.N. & Ndegwa, T. 2002. *Mapping poverty and livestock in the developing world*. Available at http://www.ilri.org/InfoServ/Webpub/Fulldocs/.

Vitousek, P.M., Ehrlich, P.R., Ehrlich, A.H. & Matson, P.A. 1986. Human appropriation of the products of photosynthesis. *BioScience,* 36: 368–373.

Wheeler, R.O., Cramer, G.L., Young, K.B. & Ospina, E. 1981. *The world livestock product, feedstuff, and food grain system.* Winrock International Technical Rep., Morrilton, Arkansas.

Wirsenius, S. 2003. Efficiencies and biomass appropriation of food commodities on global and regional levels. *Agric. Syst.*, 77: 219–255.

World Bank. 1989. *Sub-Saharan Africa: From crisis to sustainable growth*. Washington DC, USA.

WRI. 1990. *World resources 1990–1991*. World Resources Institute/Oxford University Press, New York, USA, and Oxford, UK.

SECTION III

Case studies

This section presents a number of in-depth case studies of current approaches to assessing livestock feed situations and feed balances.

First, the global growth in demand for animal-source foods is assessed using state-of-the-art databases on global changes in human populations, diets and land uses.

This is followed by perhaps the most sophisticated example of a national feed assessment system – that which has been developed in Switzerland over decades. This case study provides an example of what can be accomplished with highly developed national agricultural databases.

The case study from India provides insights into one country's approach to assessing livestock feeds in an extremely diverse set of livestock production systems involving high degrees of utilization of crop by-products.

The subsequent four case studies address spatially extensive livestock production systems in rangelands and grasslands of Africa and Asia. In contrast to the intensive systems in Switzerland and India, these systems make heavy use of remote-sensing data.

The Livestock Early Warning System (LEWS) that has been applied in the Gobi region of Mongolia goes even further in using models driven by climate and other biophysical data to assess risks of feed shortages in the near future.

This is followed by a chapter on estimating livestock feed balances, in which animal nutritional requirements are considered in more detail in relation to feed quality as well as quantity.

A chapter on the use of ecosystem simulation modelling to assess spatially extensive livestock systems integrates many of the approaches taken in previous examples while considering system dynamics and the effects of herbivory on vegetation and soils.

The concluding chapter reviews state-of-the art methodology for assessing feed situations in grasslands and rangelands.

7. Demand growth for animal-source foods: implications for livestock feed production

Tim Robinson and Harinder P. Makkar
Animal Production and Health Division, FAO, Rome, Italy
Email: Tim.Robinson@fao.org

7.1 INTRODUCTION

Each year, the Food and Agriculture Organization of the United Nations (FAO) produces its flagship publication: *The State of Food Insecurity in the World* (most recently, FAO, 2010a; FAO, 2011a). While the topical emphasis varies from year to year, the central theme is about how many people in the world are under-nourished. This number is re-evaluated each year using a food balance sheet (FBS) approach.

For a broad group of crop and livestock commodities, national estimates of the food available for human consumption are made, along with the caloric content of each commodity. These data are used to calculate total availability of calories in the country. Given that different age and sex groups have different minimum caloric requirements, data on population structure are used to estimate the total caloric requirements for the entire population. Household survey data, typically used to measure poverty, are used to estimate the country–specific distribution of calories. Then, from the total calories available, total calories needed for a given population and the distribution of calories, the number of people who fall below the minimum energy requirement is estimated. This represents the number of undernourished people.

A summary is provided below of how estimates are made of the food available for human consumption, both now and in the future. Two separate aspects of this analysis are then described, both of which point to the importance of accurate measurement and monitoring of livestock feed production: first, in the estimation of the supply and demand for the feed-crops themselves; and second, in the estimation of demand for livestock commodities and how this is expected to grow.

7.2 SUPPLY AND DEMAND FOR AGRICULTURAL COMMODITIES, NOW AND IN THE FUTURE

The approach taken to estimating the amount of food available for human consumption uses a Supply Utilization Account (SUA)[5] framework, structured as follows:

[5] Supply utilization accounts are time series data dealing with statistics on supply (production, imports and stock changes) and utilization (exports, seed, feed, waste, industrial use, food, and other use) which are kept physically together to allow the matching of food production with food available for human consumption.

Demand (total domestic use)
= food available for human consumption + industrial non-food uses + used as feed + used as seed + waste (+ discrepancy)
= production + (imports - exports) + (opening stocks - closing stocks)

A base year is selected, in which, for each commodity and country, production, demand and net trade balances are estimated. For the base year, SUAs are driven by production estimates. Net trade, feed, seed, waste and industrial use are estimated and the food available for direct human consumption is the residual. A major component of data preparation work is unravelling the SUA element production for the base year into its constituent components. The rather complex procedure is described in detail in Alexandratos (1995) but, very simply, crop production requires estimation of areas, cropping intensity and yields, and livestock production requires estimation of total stock, off-take rates and carcass weights (or yields per animal in the case of milk and eggs).

Crop production = area planted × cropping intensity × yield
Meat production = number of animals × off-take rate × carcass weight
Milk and egg production = number of animals × yield per animal

To make predictions about the future, food available for direct human consumption is projected in per capita terms using the base year data, a set of estimated food demand functions (Engel curves[6]) for each commodity in each country, and assumptions about the growth of per capita Gross Domestic Product (GDP). Estimates of economic performance are extended from the World Bank's *Global Economic Prospects 2006* (World Bank, 2006), which provides per capita GDP projections up to 2015 (Alexandratos *et al.*, 2006). The total projected food demand is then obtained by multiplying the projected per capita levels with projected population figures, taken from the medium variant *World Population Prospects 2002* revision (UN, 2003), which projects the world population to grow from the 2000 level of 6.07 billion to 8.13 billion in 2030 and 8.92 billion in 2050.

7.3 THE IMPORTANCE OF ACCURATE ASSESSMENTS OF FEED FOR CROP COMMODITIES

It was mentioned above that, in the base year, the food available for direct human consumption is estimated as the residual, having accounted for net trade, and subtracted the quantity of each commodity use for feed, seed, waste and industrial use from its estimated production. It is clear, therefore, that the more precise the estimate of each crop commodity that is destined to produce livestock feed, the more accurate will be the estimate of the food available for human consumption. To give some indication of how important the estimation of feed is, Table 7.1 provides some of the SUA data for some crops which make major contributions to feed resources in India.

Of the crops grown in India in 2000, pulses made the largest absolute contribution to feed production. However, this pattern is projected to change dramatically in the future. Projections suggest that by 2030 the production of feed will be dominated by maize: 70 percent of that grown will be used for feed. Other cereal crops, such as wheat, are also projected to become much more important for the production of feed. Because the estimation

[6] An Engel curve describes how household expenditure on a particular good or service varies with household income.

TABLE 7.1
Production, estimated feed use and percentage used as feed for selected crops in India

	2000			2030			2050		
	Prod	**Feed**	**Prop**	**Prod**	**Feed**	**Prop**	**Prod**	**Feed**	**Prop**
Pulses	13 020	1 125	8.6	14 616	1 600	10.9	14 413	2 000	13.9
Wheat	72 446	869	1.2	114 000	4 000	3.5	135 000	11 000	8.1
Raw sugar	34 092	829	2.4	56 289	1 200	2.1	68 140	1 800	2.6
Paddy rice	135 282	541	0.4	168 000	3 000	1.8	177 000	6 000	3.4
Maize	12 285	210	1.7	24 739	17 500	70.7	34 000	24 500	72.1
Millet	10 067	161	1.6	6 749	500	7.4	4 666	1 200	25.7
Barley	1 472	133	9.0	1 522	50	3.3	1 638	50	3.1
Sorghum	8 003	96	1.2	6 014	400	6.7	4 799	600	12.5
Veg. oil & oilseed	7 456	66	0.9	12 915	162	1.3	17 107	233	1.4

Note:
Prod = Production in thousands of tonnes
Feed = Estimated feed use in thousands of tonnes
Prop = Proportion in percentage
Source: data based on Alexandratos *et al.* (2006).

of the amount of food available for human consumption is heavily dependent on knowing how much of the overall production of these important staples will be used for feed, it is clear that measuring and monitoring feed production is critical for accurate assessment of the numbers of under-nourished people.

7.4 DEMAND GROWTH FOR ANIMAL-SOURCE FOODS

Driven by urbanization, population growth and increasing wealth, the demand for animal-source foods in developing countries is growing rapidly (FAO, 2010b). Livestock is one of the fastest-growing sectors in agriculture, presenting potential opportunities for economic growth and poverty reduction in rural areas. But positive social outcomes of livestock sector growth may not be ubiquitous and, in some areas, there may be detrimental social effects as small-holders dependent on livestock for their livelihoods are squeezed out from the sector by competition from larger players who can benefit from economies of scale. Beyond possible social problems are environmental, and animal and public health issues that are likely to be associated with rapid, poorly regulated livestock sector growth. Understanding where growth in demand for livestock commodities is likely to occur, and where production will rise to meet this increasing demand, are therefore important for a number of reasons. One question relates to livestock feed: Where will the additional feed resources come from?

FAO's most recent predictions on the supply and use of agricultural commodities extend previous projections from 2015/2030 (Bruinsma, 2003) to 2030/2050 (Alexandratos *et al.*, 2006). These new estimates have been used by Robinson and Pozzi (2011) to map changing demand for livestock products, and the associated changes in production that will be required to meet that growth in demand. The approach taken is to map consumption of livestock commodities based on the distributions of rural and urban populations in the base year and at chosen dates in the future. For the base year (2000), the Global Rural Urban Mapping Project (GRUMP) population map was used (CIESIN *et al.*, 2004) but was adjusted so that total number of people in each country matched those used by the FAO projections (based on UN, 2003). For the 2030 and 2050 projections, the adjusted GRUMP 2000 maps were used, and the base year population figures were multiplied by a 'growth' factor, so that the total number of people in each country matched FAO's projected figures. Urban and rural population totals for 2000, 2030 and 2050 were also estimated, based on the proportions of population living in urban areas from the United Nations' *World Urbanization Prospects* (UN, 2008). Then, for each country, the urban and rural population distributions from GRUMP were adjusted to match the UN/FAO urban and rural totals in 2000, and 'grown' separately to map future urban and rural populations.

For each time period, the national food consumption for each commodity was distributed equally among the population of each country and expressed as consumption per square kilometre. Absolute changes in consumption were then estimated for each commodity by subtracting the map of consumption estimates for the base year (2000) from those for 2030 or 2050. Table 7.2 shows changes in consumption from 2000 to 2030 for each commodity for the developing regions of the world. The results reflect changes

TABLE 7.2
Growth in demand for livestock products from 2000 to 2030

Region	Beef		Milk		Mutton		Pork		Poultry		Eggs	
	Abs	Prop	Abs	Prop	Abs	Prop	Abs	Prop	Abs	Prop	Abs	Prop
East Asia and Pacific	8 798	130	23 765	132	1 669	58	28 075	63	22 522	143	10 188	45
China	*6 888*	*132*	*15 936*	*143*	*1 537*	*56*	*22 050*	*54*	*14 609*	*121*	*6 810*	*34*
Eastern Europe and Central Asia	290	11	4 364	15	204	40	112	5	2 310	108	684	28
Latin America and Caribbean	7 302	58	39 818	72	239	54	4 405	100	14 434	126	3 246	78
Middle East and North Africa	1 929	112	17 913	111	1 287	103	9	52	6 296	243	1 799	148
South Asia	3 367	84	118 942	126	1 722	115	950	160	11 491	725	5 947	294
India	*1 338*	*51*	*79 330*	*119*	*588*	*85*	*921*	*160*	*8 865*	*844*	*4 251*	*280*
Sub-Saharan Africa	3 768	113	20 939	107	1 883	137	1 106	155	3 235	170	1 727	155
All Regions	25 454	81	225 741	97	7 004	88	34 656	66	60 287	170	23 590	70
High-Income Countries	2 441	15	31 312	31	275	33	2 935	22	12 414	65	1 911	24

Notes:
'Abs' is the absolute increase in annual consumption from 2000 to 2030 in thousands of tonnes; 'Prop' is the increase expressed as a percentage of consumption in 2000.
The regions are defined according to the World Bank 2010 classification (World Bank, 2010).
Source: Adapted from Robinson and Pozzi (2011)

both in population and in consumption patterns. The most striking factor is that growth in poultry consumption outstrips growth in all other animal-source foods in all regions of the world. By far the most dramatic change is the projected increase in demand for poultry meat in South Asia: a 725 percent increase overall. This is driven by growth in demand in India where a staggering 850 percent increase is projected over the 30-year period.

A closer look at projected growth in demand for poultry meat in India shows that the consumption of poultry meat is due to increase by 8 865 400 tonnes from 2000 to 2030. This raises important questions: Where will this additional meat come from? How will it be produced? And what resources will be required to produce it? The FAO projections do not anticipate this increase in demand to be met through imports, but through an increase in production. Furthermore, since the growth in demand will arise largely through increasing wealth and urbanization (Robinson and Pozzi, 2011), it is reasonable to assume that most of it will have to be met by a rapid intensification of the poultry sector. This in turn begs the questions: How much additional feed will that require? And how much land might be required to produce that?

A rough calculation of the feed requirements for this can be made as follows, under the broad assumption that chicken accounts for the vast majority of poultry meat in India. Based on a dressing percentage of 75 percent, and a feed conversion ratio (FCR) of 2.3 it was estimated that 27 187 227 tonnes ([8 865 400 ÷ 0.75] × 2.3) of additional feed would be required per year by 2030 compared with 2000.

The composition of broiler feed in India varies somewhat seasonally and with the price of ingredients; typical values are provided in Table 7.3, compiled from information provided in USDA (2004). Given the required weight of each ingredient, and their expected yields (year 2000 estimates from the FAO projections), the additional cropped area needed to provide each of those ingredients can then be estimated (Table 7.3).

This results in an estimated total additional cropped area of some 23.6 million hectares; a land area approaching that of the United Kingdom (24.2 million hectares[7]). In reality, however, some of the projected increase in poultry meat consumption will be met through backyard, scavenging systems that do not require any additional land. It is also likely that, as demand grows, crops grown specifically for feed will be partially replaced

TABLE 7.3
Feed composition for broiler chickens in India; crop production coefficients for the ingredients (see text for explanation and data sources) and estimates of production and cultivated area required to meet additional broiler chicken feed demand

Ingredient	Proportion (%)	Weight (tonnes)	Yield (tonnes/ha)	Area (ha)
Maize	55	14 952 975	1.8216	8 208 704
Rice	10	2 718 723	2.8507	953 704
Soybean	30	8 156 168	0.8222	9 919 932
Oilseed	5	1 359 361	0.2997	4 535 740
Total	100	27 187 227		23 618 079

Source: Robinson *et al.* (2012).

[7] www.listofcountriesoftheworld.com.

with by-products of the food industry. Other considerations are that feed or components thereof may be imported, and there will certainly be intensification in the production of the feed crops themselves. The 2000 estimates of corn yields used here are 1.81 tonnes per hectare, which is very low by most standards: 3.2 tonnes per hectare in Thailand, 4.4 China and 8 in the United States, for example (USDA, 2004). There is clearly much scope for intensification of corn production but, in semi-arid India, significant increases in yield would require irrigation, posing further questions: Where will the water come from? What will be the effects of increased rainwater harvesting in terms both of local environmental functions and broader-scale effects on water resource availability?

While representing the upper limit of increased land requirements for feed production to meet production targets for demand growth, this type of analysis shows that the required increases in the amount of land and water that will be needed to meet the growing demand for animal-source foods in the burgeoning cities of some parts of the world are likely to be immense. The land use changes required to meet these demands may considerably undermine ecosystems services not only locally, where these feed resources are produced, but on a global scale.

In this context, it would appear essential that global feed resources, particularly those destined to supply the rapidly growing, intensive production systems of the developing world, are carefully evaluated and monitored in order that appropriate policies are developed and implemented to ensure sustainable growth of the livestock sector. As management consultant Peter Drucker famously once said: **"**If you can't measure it, you can't manage it." Assessment of available feed resources will generate information on *how much* and *when* different feed resources are available, which will enable optimal policy and management decisions to be taken regarding the use of these resources. In addition, this information will enhance efficiency and profitability of the animal feed industry and assist researchers to formulate sustainable feeding strategies. Such efforts will, in turn, translate into enhanced food security. Furthermore, coping with emergency situations such as drought and floods will be facilitated by better information on the availability of feed resources. Spatial and temporal assessments of current and forecasted feed resources, including forages, will assist in disaster management and policy-making. Information on the availability and use of feed resources could also be used better to determine input-output relations as has been done for estimation of edible protein output to protein input for various countries (Table 7.7 in FAO, 2011b). Results such as these could be made much more accurate if proper feed inventory systems are in place. The estimation of feed resources could also improve the accuracy of estimates of the environmental impacts of livestock, not only through land use transformations, as discussed above, but also in the estimation of greenhouse gas emissions associated with livestock production.

7.5 REFERENCES

Alexandratos, N. 1995. *World agriculture: Towards 2010, an FAO study*. Chichester and Rome: John Wiley and Sons and Food and Agriculture Organization of the United Nations.

Alexandratos, N., Bruinsma, J., Bödeker, G., Schmidhuber, J., Broca, S., Shetty, P. & Ottaviani, M.G. 2006. *World agriculture: Towards 2030/2050*. Interim report. Food and Agriculture Organization of the United Nations, Rome, Italy.

Bruinsma, J. 2003. *World agriculture: Towards 2015/2030*. London and Rome: Earthscan and Food and Agriculture Organization of the United Nations, Rome, Italy.

CIESIN, IFPRI, WB & CIAT. 2004. *Global rural–urban mapping project (GRUMP), Alpha version*. Palisades, NY: Center for International Earth Science Information Network (CIESIN), Columbia University; International Food Policy Research Institute (IFPRI); The World Bank (WB) and Centro Internacional de Agricultura Tropical (CIAT). Available at http://sedac.ciesin.columbia.edu/gpw/.

FAO. 2010a. *The state of food insecurity in the world 2010: Addressing food insecurity in protracted crises*. Food and Agriculture Organization of the United Nations, Rome, Italy. 56 pp.

FAO. 2010b. *The state of food and agriculture 2009: Livestock in the balance*. Food and Agriculture Organization of the United Nations, Rome, Italy. 176 pp.

FAO. 2011a. *The state of food insecurity in the world: How does internal price volatility affect domestic economics and food security?* Rome, Italy. 51 pp.

FAO. 2011b. *World livestock 2011 – Livestock in food security*. Food and Agriculture Organization of the United Nations, Rome, Italy.

Robinson, T.P. & Pozzi, F. 2011. *Mapping supply and demand for animal-source foods to 2030*. Animal Production and Health Division (AGA) Working Paper 2. Food and Agriculture Organization of the United Nations, Rome, Italy.

UN. 2003. *World Population Prospects. The 2002 Revision*. United Nations, New York, USA.

UN. 2008. *World Urbanization Prospects. The 2007 Revision*. United Nations, New York, USA.

USDA. 2004. *India's poultry sector: Developments and prospects*. United States Department of Agriculture (USDA), Economic Research Service, Agriculture and Trade Report WRS-04-03.

World Bank. 2006. *Global Economic Prospects 2006*. Washington DC: The World Bank.

World Bank. 2010. *World Development Report 2010: Development and climate change*. Washington DC: The World Bank.

8. The Swiss feed balance

Silvano Giuliani and Daniel Erdin-Winkler
Swiss Farmers' Union, SFU Statistics, 5201 Brugg, Switzerland
Email: daniel.erdin@sbv-usp.ch

8.1 INTRODUCTION

8.1.1 History

In Switzerland, the Statistics Division of the Swiss Farmers' Union ("Schweizerisches Bauernsekretariat") made efforts to prepare a feed inventory in 1911–1913. But annual inventories have been conducted on a regular basis only since 1933. In the years after 1933, the inventory comprised three sections: the first specified energy needs and protein needs in starch units and digestible protein; the second determined the supply of domestic feedstuffs; and the third determined supply of imported feedstuffs. The feed inventory continued in this form until the 1970s.

A fundamental revision took place in the 1980s with the establishment of a national food plan for times of crisis. Revised time series were calculated back until 1976. Starch units were replaced by metabolizable energy for ruminants, and energy needs were calculated by form (net energy of lactation, net energy of growth, etc.) for each livestock category.

The last revision was carried out in 2008 and 2009, leading to the current method for the Swiss Feed Balance, which is presented here.

8.1.2 Purpose of the feed balance

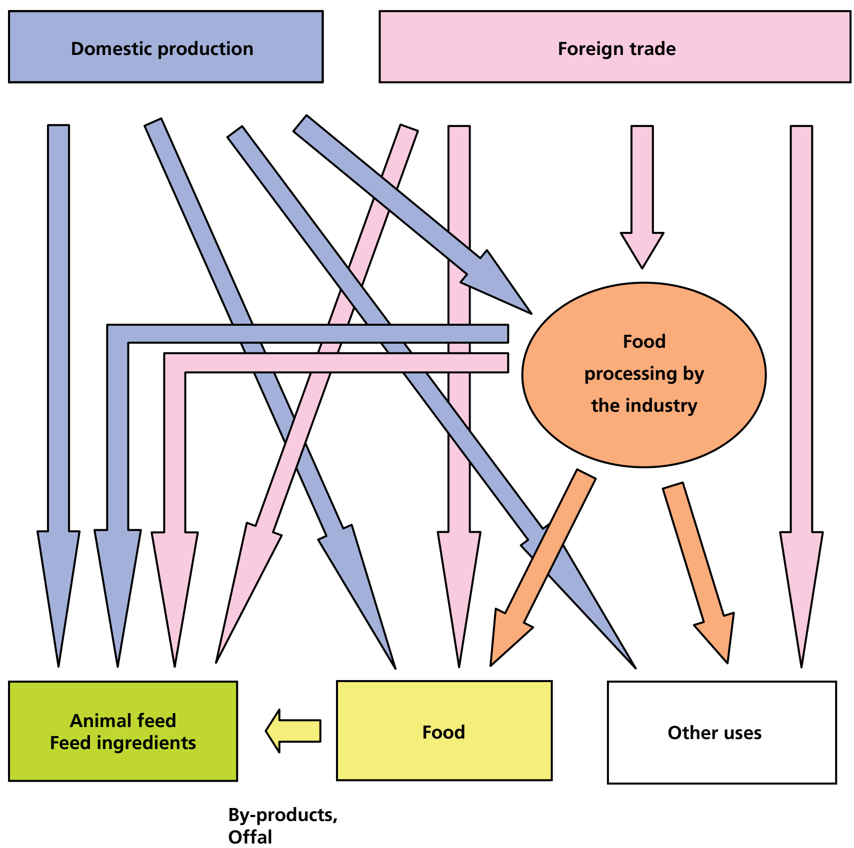
The early use of feed inventories must be viewed against the background of World Wars I and II. Switzerland was twice encircled by belligerent countries and the supply of food was often difficult. Consequently, it was essential to make an inventory of available food resources and production systems in order to optimize agricultural production. During the Cold War, this aspect of provision remained important. Even now, it has kept its importance in the framework of the "National Economic Supply" (National Economic Supply, 2011), a governmental structure for the management of supply crises. Today, different scenarios of crisis leading to feed and/or food deficiency can be imagined: severe droughts leading to poor harvests and low water levels in the Rhine River that restrict importations of bulk freight (e.g. cereals, fuel) on the waterway from the North Sea, accidents in nuclear power plants or terrorist attacks and war-like events with great impact. The revisions in the 1980s continued to be based upon these considerations.

In the meantime, many new applications have been found for the feed balance, especially in relation to emerging environmental issues: production of greenhouse gases, nutrient balances and flows of biomasses. The Swiss Feed Balance also produces relevant data to assess the economic importance of feed production for animals within the national accounting system of the Federal Office of Statistics (Swiss Statistics, 2011). However, the securing of the feed and food supply has kept its place and with regard to the 2007/2008 food crisis even won some new importance. As a conclusion, the feed balance still provides important, basic information to policy-makers.

8.2 METHODOLOGY

The basic aim of the Swiss Food Balance is to evaluate the feed available for farm animals in Switzerland, i.e. the supply. Everything that can be eaten by livestock animals is included as feedstuffs. In practice, the list of feedstuffs is limited mostly by hygienic reasons. In Switzerland, feedstuffs come from different sources. The greatest part is cultivated and harvested for this purpose (mostly forage and feed grain). Still, livestock use a multitude of products, most of which are by-products and offal from food processing. Some of these products serve as raw materials for the feed industry. The feed balance considers the feeding components before transformation and mixing through the feed industry. Figure 8.1 shows the flows of feedstuffs.

FIGURE 8.1
Flows of feedstuffs



The feed balance calculates the feedstuffs which are available for livestock animals during one calendar year from 1 January to 31 December. In addition, the needs of the livestock animals are calculated on the basis of the results of a livestock census and compared with the available offer of feedstuffs. This serves as a quality check. Important differences between the results of the two statistics have to be checked for possible errors or inaccuracies. The formula for the calculation of available feedstuffs is the same for every product:

Available feedstuffs = Domestic production – Change of domestic stocks + Imported feedstuffs – Exported feedstuffs – Imported pet food – Change of imported stocks + By-products from imported raw materials

The feed balance has a fixed framework (products, categories of livestock animals, feeding values), which is only changed during revisions, and a variable component (quantities, proportions for the distribution of the feedstuffs between animal categories), which is adapted to yearly changes. The product list and the hierarchical structure of the feed list has been established on the base of the *Handbook for compiling supply balance sheets – animal feed: supply* (EUROSTAT, 2002). The nomenclature has been expanded according to Swiss conditions. The feeds are grouped as follows:

Marketable feedstuffs:

- Feedstuffs of vegetable origin (e.g. barley)
- By-products of processing (e.g. sugar beet pulp)

Normally non-marketable feedstuffs:

- Feeding stuffs of animal origin
- Annual fodder (e.g. fodder beet)
- Perennial fodder crops (e.g. grass silage)
- Crop by-products (e.g. sugar beet leaves and tops)
- Other (e.g. offal)

The available quantity of each product is distributed among the different livestock categories, which are the same as those described in the EUROSTAT manual:

- Cattle (with cows as sub-group)
- Sheep and goats
- Pigs
- Poultry
- Other: equines, rabbits, deer (fallow or red deer)

For each product, the distribution key according to livestock categories has to be defined. First, forage (fresh grass, hay, grass silage) is distributed among forage-consuming animals. Products which are used completely for a certain livestock category are assigned. After that, other products are distributed according to information from the feed industry. At this point, a first check takes place: the quantities are compared with the needs for each livestock category. If necessary, the distribution is corrected. As soon as the quantities fit, the quantity of energy and protein distributed to each category is also compared with the needs. This check is not easy to interpret because the quality of forages can widely vary from one year to another.

The various feedstuffs have very different properties. An aggregation can only be made if a common denominator can be found. The most important measurement unit is therefore dry matter. Additionally, gross energy and crude protein are considered. Appropriate feeding values are used for each livestock category:

Cattle, sheep and goats

- Metabolizable energy for ruminants
- Net energy of lactation
- Net energy of growth
- Absorbable protein in the intestine

Pigs

- Digestible energy for pigs
- Crude protein

Poultry

- N-corrected metabolizable energy for poultry
- Crude protein

Other

- Digestible energy for horses
- Digestible protein for horses

The publications of the Swiss Agroscope Liebefeld-Posieux research station have been used as the source for feeding values. The feeding values are only changed within revisions. The values are registered in a database and linked to the different products on the feedstuff list.

The annual data of the feed balance are compiled in a database. Foreign trade data are directly imported from the corresponding database. Other data have to be entered manually. An existing project that has developed a food balance database could also serve as a source for the by-products of food processing. In the meanwhile, those data must also be entered manually.

8.3 SOURCES FOR ANNUAL DATA

Foreign trade data (importation, exportation, pet food) come from the Swiss Federal Customs Administration. All products which are imported for feeding purposes and thus declared are considered. Exported feedstuffs and pet food have to be discounted from the resulting importations. The product list of the customs administration is more elaborate than the product list of the feed balance. Therefore, one product of the feed balance can match with multiple products of the foreign trade list.

Information for domestic production has several sources:

- The indications for feeds of vegetable origins come from production statistics (pulses), from the enterprise balance (potatoes, cereals) or estimations from SFU Statistics (oil seeds, processed forage).
- By-products of food processing: information from the industry or estimations from SFU Statistics. The milling industry has its own statistics for Switzerland which cover by-products. By-products of the brewing industry are estimated on the basis of the beer production as indicated by the brewing industry. The amount of sugar produced by the sugar manufacturing units provides information about the production of sugar beet pulp. The quantities of pomace (apples, pears) are surveyed by the Federal Office for Agriculture. The by-products of oil production are estimated on the basis of production and appropriate rates of yield.

- Feedstuffs of animal origin are almost completely prohibited in Switzerland. The quantity of milk products used for livestock is estimated on the basis of milk production statistics elaborated by SFU Statistics together with the milk sector.
- Quantities of fodder beets are taken from production statistics and those of green and silage maize from forage statistic (SFU Statistics).
- Quantities of perennial fodder come from forage statistics (SFU Statistics).
- Crop by-products (mostly stems and leaves of sugar beets) are estimated on the basis of production statistics.
- Other feedstuffs (vegetables, fruits, offal) are estimated by SFU Statistics.
- Fodder maize and grassland forage production are estimated by SFU Statistics.

By-products from the food processing of imported raw materials are calculated using the same methods as used for calculating by-products derived from domestic raw materials (e.g. from vegetable crops, as above).

The final component is the change of stocks of domestic and imported feedstuffs. There is no systematic survey and SFU Statistics uses only the data of Réserve Suisse, the responsible organization. For domestic products, only the stocks of cereals, pulses and oil cakes are entered. For imported products, stocks of rice (broken), oil seeds and by-products of starch production are also entered.

It is not always easy to separate pet food from the feedstuffs for livestock. This is especially true for domestic production because no data are available. However, those quantities should not be very significant.

8.4 FORAGE (ROUGHAGE) CALCULATION

Forage calculation is based on production statistics for fodder maize and grass (fresh, hay, silage, artificially dried) produced annually by SFU Statistics. The following terms are used for forage production:

- Gross yield = surface biomass
- Yield in the field = harvested yield – field losses
- Net yield = yield in the field – losses due to conservation

The terms for utilization of forage are:

- Consumption of forage = net yield fed to livestock in the reported year
- Ingestion of forage = consumption of forage – feeding losses (wastage)
- Forage needs = quantity of forage necessary for covering maintenance, growth, production and gestation of livestock animals

The following is the set of parameters that is used for estimating forage production (production approach):

- Altitude of the areas used for forage production and the corresponding production potential
- Area used for forage production based on area data of SFU Statistics
- Estimated yields based on surveys of SFU Statistics
- Dry matter content and quality of forage plants
- Meteorological conditions

Production is estimated for the calendar year according to the type of area as follows:

Production = area x annual yield/area unit

Areas are classified according to the official production zones: plains, hills, mountains I-IV. The areas and the production zones come from SFU Statistics. The average yields are estimated from standard yields that are reported by SFU Statistics. The standard yields are then corrected for meteorological conditions, as determined in part from data collected in regular surveys. The estimated production of fresh matter is converted to dry matter.

In parallel, the quantity of forage is also estimated on the base of utilization (utilization approach). The corresponding factors of influence are:

- Duration of green fodder period
- Utilization of forage
- Dry matter intake of livestock animals
- Duration of pasture season in mountain regions (alps)
- Capacity for forage stocks (hay, silage)
- Losses in the field through conservation, during feeding

The utilization approach estimates forage consumption in a calendar year. This approach calculates consumption according to the type of forage. Maize is subdivided into green maize and maize silage. Grass is grouped according to utilization or conservation type: alpine pastures, other pastures, fresh grass (fed in the barn), artificially dried grass, hay (first and following cuts) and grass silage. Some of those products are further subdivided according to quality.

While the production approach covers only domestic production, the utilization approach also considers imported forage. The difference between the production and utilization approaches results in the quantity which must be imported or covered by stocks. For a period of several years, there has to be a balance between production and utilization, which takes the following form:

Forage balance of the actual year = yield in the field – losses from conservation + excess of forage of the preceding year – shortage of forage of the preceding year + excess of imported forage (almost no forage is exported) – forage consumption by livestock animals

The result is often positive in good years and mostly negative in bad years is. A balance of inputs versus outputs should be obtained over a period of several years. Because the same grassland can be exploited several times a year, the assignment of conservation type is somewhat arbitrary and is controlled by calculated needs.

8.5 ESTIMATION OF NEEDS

"Estimated needs" is the check value on the estimated available quantity of feedstuffs. It incorporates effects of quantity and the quality of forage. It is especially useful in that it distributes available quantities according to livestock categories (Table 8.1).

The needs of the livestock animals are calculated according to the feeding recommendations of the research station Agroscope Liebefeld-Posieux. Some of those recommendations are taken from the "Wirzkalender" (Agridea, 2011), a handbook for farmers. For every livestock category the needs for dry matter, energy and protein are estimated. Energy and protein needs are calculated in the appropriate unit for each livestock category.

There is no single measurement unit that can be used for every livestock category. Units (number of animals, fattening days and so on) are particular to each kind of animal.

TABLE 8.1
Measurement units for the estimation of the needs according to livestock categories

Livestock category	Livestock unit	Energy unit	Protein unit
Cattle, maintenance and breeding	Number of cows and bulls	Net energy of lactation	Absorbable protein in the intestine
Cattle, gestation	Number of cows	Net energy of lactation	Absorbable protein in the intestine
Cattle, milk production	Tonnes of fat corrected milk	Net energy of lactation	Absorbable protein in the intestine
Cattle on alpine pastures	Days of alpine pasture	Net energy of lactation	Absorbable protein in the intestine
Fattening calves	Days of fattening	Metabolizable energy	Digestible protein
Other cattle	Days of fattening/ growth	Net energy of growth/ lactation	Absorbable protein in the intestine
Sheep, breeding animals	Number of breeding animals	Net energy of lactation	Absorbable protein in the intestine
Sheep for fattening	Days of fattening	Net energy of growth	Absorbable protein in the intestine
Goats, breeding animals	Number of breeding animals	Net energy of lactation	Absorbable protein in the intestine
Goats for fattening	Days of fattening	Net energy of lactation	Absorbable protein in the intestine
Pigs, breeding animals	Number of breeding animals	Digestible energy	Crude protein
Pigs for fattening	Number of fattening animals	Digestible energy	Crude protein
Poultry	Tonnes of feedstuffs	Metabolizable energy	Crude protein
Equines	Number of animals	Digestible energy	Digestible protein
Rabbits	Tonnes of feedstuffs	Digestible energy	Crude protein
Other ruminants	Number of animals	Net energy of growth	Absorbable protein in the intestine

As already noted above, the delimitation of pet food is sometimes difficult. Official livestock statistics exclude the animals of pet owners and livestock owners with few animals and little cultivated area. Generally, pet animals are not imported but they have some weight in the categories of rabbits and equines.

8.6 CALCULATION AND PUBLICATION

SFU Statistics calculates the annual feed balance once a year. The provisional feed balance for year t is calculated at the end of year t + 1. If necessary, the feed balance for year t - 1 is revised.

The results of the feed balance are published every year in *Statistical censuses and estimations in agriculture and nutrition* (USP, 2009). The results are presented in three tables:

- Table1: Product list with the results of several years and quantities of fresh matter, dry matter, gross energy and crude protein.

- Table 2: Product list with the origin of the feedstuffs and quantities of fresh matter, dry matter, gross energy and crude protein for one year.
- Table 3: Utilization of the feedstuffs for several years according to livestock categories with dry matter and appropriate feeding values for each livestock category.

Estimated needs are no longer published. They serve exclusively as check values and as an aid in the process.

8.7 REFERENCES

Agridea. 2011. *Wirz Kalender 2011. A set with two handbooks*. ISBN 978-3-7245-1656-9

EUROSTAT. 2002. Office for Official Publications of the European Communities. 2002. *Handbook for compiling supply balances sheets – animal feed: supply*. ISBN 92-894-3741-3.

National Economic Supply. 2011. *Homepage.* Available at www.bwl.admin.ch/index.html?lang=en.

Swiss Statistics. 2011. *National economy site*. Available at www.bfs.admin.ch/bfs/portal/en/index/themen/04.html.

USP (Union Suisse des Paysans). 2009. *Statistische Erhebungen und Schätzungen (Statistiques et evaluations concernant l'agriculture et l'alimentation).* Union Suisse des Paysans, USP Statistique. Brugg, Switzerland.

9. The Indian feed inventory

Samireddypalle Anandan and Koratikere T. Sampath
National Institute of Animal Nutrition and Physiology (ICAR), Adugodi, Bangalore-560 030, India
Email: anandsrp@yahoo.co.in

9.1 INTRODUCTION

9.1.1 Rationale

Numerous studies have shown that shortages of feed resources have been major constraints in improving livestock productivity in India. In spite of this, feed resource assessments have received little attention, which is evident from the fact that no public or private sector agency produces national or regional information on feed resources. Updated information on availabilities and requirements is important not only for short- and long-term planning but also for ensuring national food security. Over the years, there has been a continuous debate on the livestock feed situation in India and some researchers have made attempts to quantify animal feed resource availabilities and requirements (Sen and Ray, 1941; Mudgal and Pradhan, 1988; Sampath *et al.*, 2005). All studies conducted so far have consistently shown that requirements exceed availabilities, and it is likely that the gap will further widen in the future. But these projections of deficits have to be viewed with a certain degree of circumspection and reservation. This is especially true given that milk, egg and meat productivities in India have consistently increased over the last two decades. These increases could not have been solely due to increases in livestock numbers; improvements in overall feed availability have no doubt also been important. It is against this background that the National Institute of Animal Nutrition and Physiology in Bangalore undertook a systematic study to assess the availabilities and requirements for feed resources in different states of India.

A feed inventory of a particular area/region will provide information on the type of feed resources available and their quantities, which can then be compared with available livestock numbers to arrive at the status of the area/region in terms of whether feed availability is sufficient, in surplus or in deficit. This kind of information can be of enormous assistance for policy-makers, concerned government departments, NGOs and development agencies in formulating and implementing meaningful livestock development activities and tackling natural calamities such as drought and floods. For example, improving livestock production by improving the germplasm of animals and by improving veterinary care is only possible when there are adequate feed resources. This can only be known by carrying out assessments of feed resources. Such assessments can also help livestock traders, feed companies and commerce ministries in making informed decisions with respect to the nature and quantities of commodities, the feed resources that could be traded locally, potential areas for feed markets, and the nature and the quantities of feed resources involved in imports and exports.

9.2 METHODOLOGY

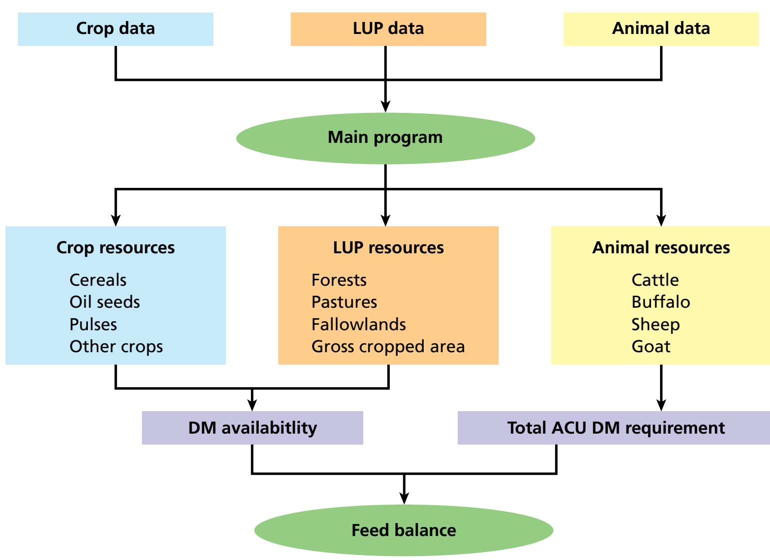
9.2.1 Inputs

There are basically three major inputs required for assessing feed resources and feed balance: i) feed resources from crop data; ii) green fodder from land classification data; and iii) feed requirement from livestock censuses.

To arrive at the availability of feed resources from crops, it is necessary to know the harvest indices and extraction rates of different products and by-products from crop production data. The harvest index is the ratio of tonnes of utilizable crop by-product to tonnes of primary crop harvested, for example tonnes of wheat straw per tonne of wheat grain. The extraction rate is the fraction of harvested primary crops used for feed, for example the tonnes of wheat grain used for feed to total tonnes harvested. Similarly, the average production potential of cultivated fodder, extent of land under fodder, average biomass production potential of other land categories must be known to arrive at total green availability. For those categories where information is lacking, efforts are made to consult with subject matter specialists and fill the gap by recording the true values. For assessing feed requirements, data is required from a livestock census that gives a detailed breakdown in terms of age groups and production functions (milk, meat, draught).

Generally, crop production and land utilization pattern data are published annually while the livestock census is carried out periodically. In India, the census takes place every five years and the annual figures can be arrived by simple calculations based on the latest census figures and the compounded annual growth rate for each category of livestock. The crop production data, land utilization data and livestock census data for a particular region for the same period must be matched to arrive at the status of feed resources availability. The structure of the program that integrates and processes the input data is show in Figure 9.1.

FIGURE 9.1
Flow chart for the database program



Source: Ramachandra *et al.*, 2007.

Input 1 – Crop production data

Using the worksheet in Table 9.1, different feed resources – straws (crop residues), grains, bran, husk and oilcake (concentrate) – can be calculated from the production data of different crops. As an example, for every 100 tonnes of wheat grains produced, 100 tonnes of wheat straw would be produced (100 multiplied by the harvest index of 1.0), the proportion of wheat grains used for feeding would be 2 tonnes (100 multiplied by the extraction rate of 0.02) and wheat bran availability would be 8 tonnes (100 multiplied by 0.08). Similarly the availability of groundnut haulms and groundnut cake for every tonne of groundnut would be 2 tonnes of haulms (1 multiplied by 2.0) and 0.7 tonnes of groundnut cake (1 multiplied by 0.70). The dry matter content of all the above feed resources is considered as 90 percent except for sugarcane tops which are high in moisture and where it is assumed that the dry matter content would be 25 percent.

TABLE 9.1
Harvest indices* and extraction rates used in the calculation of feed resources from crop production data in India

Crop production	Harvest index		Extraction Rate	
	Crop residues	Oilcakes	Grains	Bran/husk
Paddy	1.3	-	0.02	0.08
Wheat	1.0	-	0.02	0.08
Sorghum	2.5	-	0.05	-
Pearl millet	2.5	-	0.05	-
Barley	1.3	-	0.10	-
Maize	2.5	-	0.10	-
Finger millet	2.0	-	0.05	-
Small millets	2.5	-	0.10	-
Other cereals	2.0	-	0.10	-
Total Pulses	1.7	-	-	0.03
Groundnut	2.0	0.70	-	-
Sesamum indicum seeds	-	0.70	-	-
Rape & mustard	-	0.70	-	-
Linseed	-	0.70	-	-
Niger	-	0.70	-	-
Sunflower	-	0.70	-	-
Safflower	-	0.70	-	-
Soybean	-	0.70	-	-
Sugarcane	0.25	-	-	-
Coconut	-	0.0625	-	-
Cotton	-	0.0499	-	-

* Harvest index is the ratio of tonnes of utilizable crop by-product to tonnes of primary crop harvested.
Source: Ramachandra *et al.*, 2007.

Input 2 – Land utilization pattern

For assessing green fodder availability, the following factors which represent the average biomass production potential per unit hectare are extracted from the land classification data. Land utilization pattern data has the following categories – gross cropped area, forest area, permanent pastures, cultivable waste lands, current fallows, other fallows and area under miscellaneous tree crops from which green fodder is available for feeding livestock.

In the case of areas under fodder cultivation, it is assumed that 4 percent of the gross cropped area is under fodder cultivation and the average fodder yield would be 40 tonnes/hectare/year. Thus, multiplying 4 percent of the gross cropped area by 40 tonnes (0.04 X 40) gives 1.6 tonnes/ha/year. In the case of forests, because it is assumed that only 50 percent of the forests are available for fodder production and the average fodder yield is around 3 tonnes/ha/year, the factor of 1.5 tonnes/ha/year is used (0.5 X 3). For the remaining categories, the calculation is straightforward and the different factors are presented in Table 9.2. The green yield is on a fresh basis and average dry matter content of green fodder is assumed to be 25 percent.

Input 3 – Livestock census

For calculating feed requirement, detailed livestock census data are required, including estimates of age class distributions. A rough estimate of the quantitative adequacy is the first step and this can be done by assessing the requirements in terms of dry matter. Dry matter requirements of ruminants (cattle, buffalo, sheep and goats), equines and camels are calculated on the basis of a standard adult cattle unit (ACU) of 350 kg body weight, utilizing the conversion factors for species and age class (Table 9.3). Assuming that a minimum dry matter intake of 2 percent of body weight would be sufficient, an ACU would require 7 kg (350 X 0.02) of dry matter per day. Accordingly, the total dry matter requirement can be calculated by converting the livestock numbers into ACUs. The feed balance can be derived by combining total potential feed availability with total requirements.

TABLE 9.2
Green fodder yields for land use classifications

Land use category	Green fodder (tonnes/ha/year)
Gross cropped area	1.6
Forests	1.5
Permanent pastures	5.0
Cultivable waste lands	1.0
Current fallows	1.0
Other fallows	1.0
Miscellaneous tree crops	1.0

Source: Ramachandra *et al.*, 2007.

TABLE 9.3
Conversion factors for calculating adult cattle units (ACUs)

Species	Category	Conversion factor
Buffalo	>2.5 years	1.14
	1.0–2.5 years	0.50
	<1.0 year	0.17
Cattle	>2.5 years	1.00
	1.0–2.5 years	0.34
	<1.0 year	0.11
Sheep/goat	>1.0 year	0.10
	<1.0 year	0.03
Equines	>3.0 year	0.57
	<3.0 year	0.33
Camels	>4.0 year	1.00
	<4.0 year	0.57

Source: Ramachandra *et al.*, 2007.

9.2.2 Data integration

Once the data on crop production, harvest indices for various feed resources, land utilization pattern and average biomass production potential of different land categories are available, it is possible to calculate the total potential feed availability in a region. Similarly the feed resource requirements for all livestock in a region can be calculated based upon the detailed species and age-specific census data. For each species and age class, nutrient requirements are calculated in terms of dry matter, protein and energy requirement for a given population. From the protein and energy requirements for different categories of livestock, the feed resources requirements in terms of green fodder, crop residues and concentrates can be deduced in relation to the prevailing feed practices. Feed availability and requirements are calculated using a program developed in Microsoft Access or Excel.

The complete stepwise approach for establishing a regional feed inventory is as follows:

1. Obtain the necessary data on total crop production for the region from the concerned department or from agricultural statistics; usually the information is published annually in the form of reports either in hardcopy or posted on the respective department web sites.
2. From the crop production data, list all the crops and their by-products that are used for feeding livestock.
3. Prepare a list for harvest indices and extraction rates, which are proportions of crop and crop by-products used for livestock feeding; for some resources, the information may be missing and for those products the factors can be determined with the help of the experts from the concerned crop or processing sector.

4. Because the feed resources originating from crops constitute the major feed resources, the list of crops and their extraction rates should be as exhaustive as possible to account for all resources (as shown in Table 9.1).
5. Potential available feed resources can be deduced from crop production data using harvest index and extraction rates.
6. Generally the dry matter content of crops and crop-based products is around 90 percent and the same value can be used to determine total dry matter availability.
7. Additional information in terms of import/export of resources and alternate uses of resources if available should be accounted for to improve the precision of assessment.
8. The proportion of cropped area used for fodder cultivation and the average production of fodder should be known in order to estimate green fodder production.
9. For green fodder production from categories other than cultivated fodders, the land utilization pattern should be known; the area of land under different categories must be multiplied by the average production potential of green fodder to establish total green production (as shown in Table 9.2).
10. The dry matter content of green varies and average dry matter content is assumed to be 25 percent to establish total available dry matter.
11. Adding the total feed resources from crops and greens gives the total potential feed availability in a region.
12. The requirements of feed for ruminants, equines and camels can be assessed by converting the different species and categories of animals into adult cattle units based on ACU conversion factors as indicated in Table 9.3.
13. Total annual feed requirements can be calculated from the total ACU by multiplying the total ACU by 365 (number of days in year) and 7 (assuming 2 percent dry matter intake [DMI] for an ACU weighing 350 kg body weight).
14. Comparing the total feed availability with the requirement gives the status in terms of sufficiency, deficiency or surplus for that particular region.
15. A region can be classified based on the dry matter availability and generally a dry matter availability of less than 2 percent can be considered as deficit, dry matter availability between 2 and 3 percent can be considered as adequate, and above 3 percent can be considered as surplus.

The above approach is a simplified version in which only the quantitative feed-adequacy is determined for ruminants, equines and camels. The requirements of other species of livestock such as poultry, pigs, etc. can be added to total requirements and the feed balance can be derived. The approach provides a framework which can be expanded to include more details for assessing the quantitative feed adequacy for all species of livestock.

Assessing the quantitative and qualitative feed requirements precisely requires detailed information with regard to the census (age and function classes [in milk, dry, draught, breeding, etc.]) and the nutrient requirements for age and function classes, average productivities, average body weights, etc. After assessing the total nutrient requirements in terms of dry matter, protein and energy, the nutrient content of the available feed resources and prevailing feeding practices must be factored in to arrive at the feed balance. Some basic knowledge of animal nutrition with regards to the nutrient requirements of livestock and nutrient profile of feed resources is essential for carrying out this exercise, or alternately, animal nutritionists can provide the data necessary to calculate the precise feed balance.

9.3 UPDATING THE INVENTORY

The tasks associated with maintaining and updating the inventory include updating changes associated with crop production, land utilization pattern and the livestock census. While the data on crop production and land utilization pattern changes are available annually, the livestock census is carried out at periodic intervals and the annual figures can be calculated using the latest census data and the compounded annual growth rate. Further addition of newer feed resources (if any), changes in extraction rates of any of the by-products due to changes in processing, and changes in export/imports must be accounted for. A large number of agro-based by-products and species of livestock like aquaculture and pet animals have been left out in the assessment and these need to be included. Further, assessment and refinement is a continuous process and the information needs to be updated and refined as new information becomes available.

Finally, the precision of assessment can be judged by relating the total livestock numbers and livestock produce with total feed resources availability. This is based on the fact that if a particular number of livestock and quantity of livestock produce has been achieved, the feed resources for the maintenance requirements of that livestock and livestock produce must be accounted for. The closer the requirements for maintaining and producing livestock produce and availability in terms of total feed resources, the better is the accuracy. A large gap between availabilities and requirements indicates that there is scope for improving the assessment.

9.4 REFERENCES

Mudgal, V.D. & Pradhan, K.1988. Animal feed resources and current patterns of utilization in India. *In Proceedings – Symposium on non-conventional feed resources and fibrous agricultural residues: strategies for expanded utilization.* Hisar, India. pp.139–146.

Ramachandra, K.S., Taneja V.K., Sampath, K.T., Anandan,S. & Angadi, U.B. 2007. *Livestock feed resources in different agro-ecosystems of India: Availability, requirement and their management*. National Institute of Animal Nutrition and Physiology, Bangalore, India.

Sampath, K.T., Ramachandra, K.S. & Anandan, S. 2005. Livestock feed and fodder resources of India and strategies for their judicious utilization. *Indian J. Anim. Sci.* 75:1438–44.

Sen, K.C. & Ray, S.N. 1941. Animal husbandry and crop planning in India. *Science and Culture* 6:684–89.

10. Pastoral surveillance system and feed inventory in the Sahel

Frédéric Ham and Erwann Fillol
Fundación Acción Contra el Hambre, ACF-Spain, C/ Caracas 6, 1°, 28010 Madrid, Spain
Email: f.ham@achesp.org

10.1 INTRODUCTION

The Sahelo-Saharian region is characterized by vast grazing areas and high spatio-temporal rainfall variability. A large fraction of the human population subsists on extensive livestock systems characterized by extensive inter-seasonal movements linked to the availabilities of two natural resources – water and pasture.

The expansiveness of the pastoral spaces, the difficult access to pastoral resources and the very low demographic density require a different mode of food security and population vulnerability monitoring from that in areas where livestock are sedentary. In this setting, GIS and remote-sensing data must be employed because they enable efficient monitoring of pastoral resources. Pastoral food security is dependent on livestock and thus the livestock feed balance in the region.

Over several years, ACF International (Action Contre la Faim), together with the national early warning systems in Mali and Niger, has developed a Pastoral Early Warning System consisting of GIS-based tools that assess pastoral population vulnerability. Recent improvements in the system make it possible to assess pastoral population vulnerability on a regional scale, contributing to early warning systems in Sahelo–Saharian pastoral areas.

10.2 INPUTS

10.2.1 General

The Pastoral Early Warning System developed by ACF has the potential to contribute to livestock feed inventories in the Sahelo-Saharian areas because it is specifically designed to monitor feed availability for pastoral livestock. The system makes extensive use of near real-time satellite imagery, ground data validation and livestock movement maps. Computer-based tools produce user-friendly maps which enable quantitative, dynamically changing feed assessments. The system has proved to be quite efficient in recent years for identifying vulnerable situations for pastoralists, but there is still room for further improvements.

10.2.2 Remote-sensing data

The pastoral early warning system developed by ACF utilizes NDVI (Normalized Difference Vegetation Index) and DMP (Dry Matter Productivity) data products that are distributed by the Flemish Technologic Research Institute (VITO). These products are derived from the moderate-resolution VEGETATION sensors on the SPOT 4 and SPOT 5 satellites launched in 1998 (Table 10.1). Daily imagery is produced on a global scale at 1 km x 1 km resolution. In

TABLE 10.1
SPOT-VEGETATION spectral bands

Bands	Colour	Wavelengths
B0	Blue	0.430–0.740 mm
B2	Red	0.610–0.680 mm
B3	Near Infra-Red (NIR)	0.780–0.890 mm
SWIR	Short Wave Infra-Red (SWIR)	1.580–1.750 mm

order to eliminate the cloud cover, a compositing operation is realized over a 10-day period giving decadal synthesis: three decades per months (1–10, 11–20, 21–end of concerned month) and 36 decades a year.

The algorithm details can be found on the following web pages:

- http://web.vgt.vito.be/documents/BioPar/g2-BP-RP-BP053-ProductUserManual-DMPV0-I1.00.pdf
- http://www.vgt4africa.org/PublicDocuments/S10-NDVI-Product-Sheet.pdf

10.3 METHODOLOGY

10.3.1 General

The ACF's system employs a GIS overlay approach that integrates spatial data which characterize pastoral physical resources and livestock movements. The system assesses gross biomass production as well as the accessibility of the biomass in relationship to water availability and pastoral movements throughout the seasons (Figue 10.1). In the north Sahel, biomass is the primary variable which must be considered when quantifying feed availability, given that forage is directly derived from biomass.

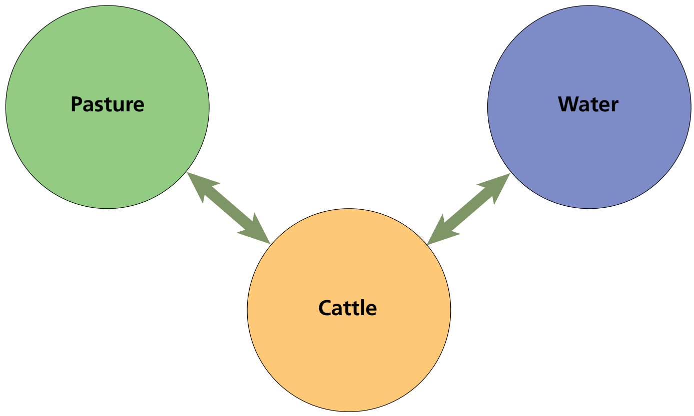
Depending on the area and the season, water may or may not be available within a feasible proximity to the grazing areas. Cattle must move to access water at sufficient frequencies while also accessing pasture. Therefore, monitoring of water availability and livestock movements to pastures are both fundamental to an accurate feed inventory. Biomass and water are integrated with additional variables such as livestock distributions and topography to produce assessments of forage availability.

10.3.2 Two-step process

Two basic steps are required in the feed inventory:

1. Biomass monitoring
2. Map overlaying
   a. Water maps
      i. Surface water
      ii. Wells and boreholes
   b. Concentration areas mapping
   c. Livestock distribution maps
   d. Topography

FIGURE 10.1
Integration of pasture, water and cattle distribution map data



10.3.3 Biomass monitoring and the BioGenerator Tool

In the north Sahelian context, the pasture growing season ends a few weeks after the end of the rainy season, occurring in autumn. After that, it is possible to determine the pasture balance of the area for the current year. A computer-based tool integrating satellite images has been developed by ACF called *BioGenerator*. This tool enables the calculation of available vegetation matter throughout the whole region at the end of the rainy season. The resulting outputs are the total dry matter production of the year, expressed as kg of dry matter per hectare, and the departure from the inter-annual average, called anomaly of dry matter production expressed in percentage.

The following is excerpted from an unpublished user manual written by E. Fillol.

Folder structure

The folder structure of input and output data is shown in Figure 10.2a. The *In* folder contains the input data while the *Out* folder receives output data.

Input data

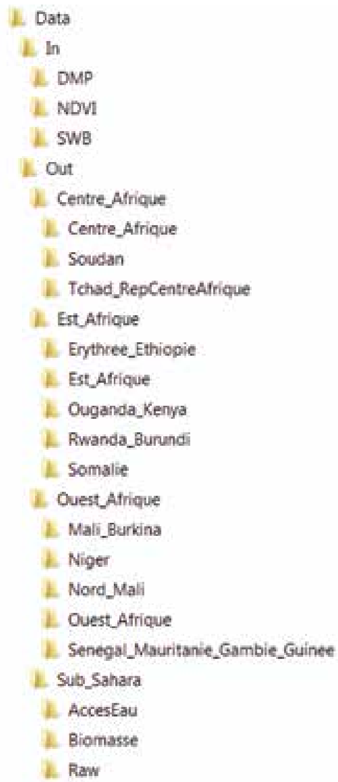
VITO provides ACF-Spain with a specific decadal data product called DMP (Dry Matter Productivity). These data are automatically loaded onto the ACF-Spain server. Access to the data is through the following contacts:

- Alejandro Canet Rodriguez : acanet@achesp.org
- Frédéric Ham : f.ham@achesp.org

The first step consists of loading the data via ftp protocol, unzipping the archives and copying them into the appropriate folder. Two fields are necessary to perform the processing: DMP and NDVI (Table 10.2).

The unzipped DMP and NDVI files are copied respectively into folders *Data/In/DMP/* and *Data/In/NDVI/*. The .img files are the image data in raw format and .hdr files are the header files.

FIGURE 10.2a
Work Folder structure of BioGenerator 2 (v2.1)



BioGenerator 2 (v2.1) can function if one or more decades are missing. In this case, a message identifying the missing decades will warn the user but the calculation will be processed. The value of missing decades will then be linearly interpolated.

BioGenerator parameters

The parameters that can be changed by the user include the following:

- Biomass anomaly spatial filter function parameters. These parameters are the size and the number of passes of this circular filter. The first number gives the number

TABLE 10.2
Zipped and Unzipped folder nomenclature and file size

Products	Zipped archives	Unzipped archives	Destination folder	Image file size .img [bytes]
DMP	DMP_aaaammjj.zip	DMP_aaaammjj.img DMP_aaaammjj.hdr	Data/In/DMP/	56 925 660
NDVI	NDVI_aaaammjj.zip	NDVI_aaaammjj.img NDVI_aaaammjj.hdr	Data/In/NDVI/	28 462 830

of passes of the filter and the second gives the radius in pixels of the filter window. The filter can also be deactivated. This biomass anomaly map filtering quickly shows local anomaly variations.

- The integration period is defined by the first and last decades. The input values are the decade's position between 1 and 36 (see Table 10.3). In the event that the last decade's value is higher than the first decade's value, the integration goes until the next year's decade. For example, default values 7 and 6 mean the integration calculated for year x is done from decade 01/03 of year x until decade 21/02 of year x+1 (as in Table 10.3). The integration period must be equal to or higher than two decades.

These parameters are accessible by the user and can be modified. Otherwise, default values will be used along with the decade's start date.

Program execution

The program is executed and an execution window opens showing the used parameters, the used decades and the number of years that are considered from this series (Figure 10.2b).

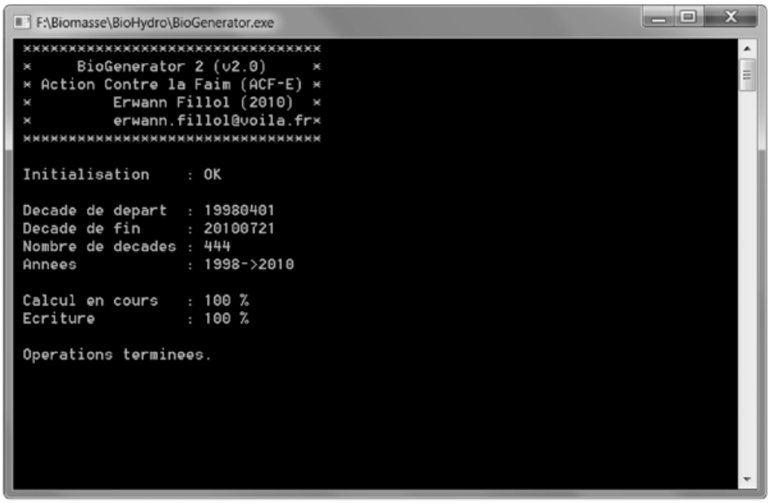
A counter shows the progress of the calculation in percent. Two calculation phases follow one another: the first phase is the calculation on the global sub-Saharan window. The second phase processes the output windows and sub-windows and performs output file writing.

Depending on the number of decades, the processor and hard disk speed, the calculation can take two to three hours on a standard PC. The minimum required configuration mainly concerns the RAM available with a minimum of 1 GB and also disk space with a minimum of 3 GB per years considered.

TABLE 10.3
Matching between decade number and decade start date

Decade number	Date	Decade number	Date	Decade number	Date
1	01/01	13	01/05	25	01/09
2	11/01	14	11/05	26	11/09
3	21/01	15	21/05	27	21/09
4	01/02	16	01/06	28	01/10
5	11/02	17	11/06	29	11/10
6	21/02	18	21/06	30	21/10
7	01/03	19	01/07	31	01/11
8	11/03	20	11/07	32	11/11
9	21/03	21	21/07	33	21/11
10	01/04	22	01/08	34	01/12
11	11/04	23	11/08	35	11/12
12	21/04	24	21/08	36	21/12

FIGURE 10.2b
BioGenerator 2 (v2.1) execution window



Output data

BioGenerator produces biomass quantity, expressed in kg of dry matter per hectare [kg.ha^{-1}] for each year and also for the mean value of the calculation period. It also produces annual anomalies [percent] on 13 different geographic windows. The output data are in GEOTIFF (.tif) format in geographic coordinates Lat/Lon WGS-84 with a spatial resolution of 1 km. Table 10.4 shows the definitions of these geographic windows.

Biomass quantity

A file is produced for each geographic window and sub-window containing the biomass quantity produced for the year, and another file is produced containing the mean value for the entire time series. Biomass is expressed in kilograms of dry matter per hectare [kg.ha^{-1}]. Null productivity is reported in desert areas and water. The annual biomass quantity is calculated as the sum of daily productivity during the growing season [kg.ha^{-1}.day^{-1}]. The growing season can be defined by the user. By default, it starts with the first decade of March and ends with the last decade of February of the following year.

The data set for the current year's growing season might be incomplete. If some decades are missing the biomass quantity calculation period is completed for the missing period using the observed average productivity. The biomass quantity map (Figure 10.3) for the current year (e.g. 2010) is an estimation of the total production dependent on the available decades.

Biomass anomaly

An output file is produced for each window and sub-window providing the biomass production anomaly (Figure 10.4), which is the difference between the biomass productivity of the year and the mean value calculated for the whole time series. The anomaly is expressed in percent.

TABLE 10.4
Coordinates of geographic windows and sizes of windows in pixels of BioGenerator 2 (v2.1) output data

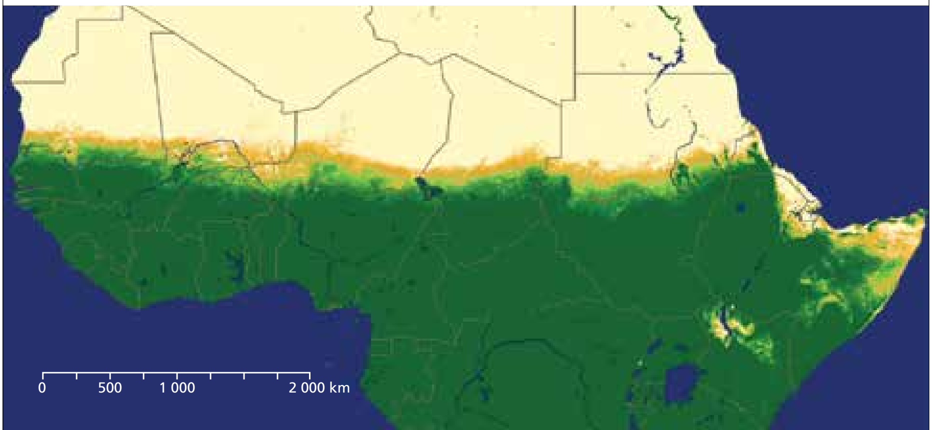
Window	Sub window	Upper left	Lower right	Size (pixels´rows)
Sub-Saharan	Sub-Saharan	-18.000E 27.375N	52.000E -5.02678611N	7841 × 3630
West Africa	Ouest_Afrique	-18.000E 27.375N	16.000E 9.000N	3810 × 2060
	Mali_Burkina	-12.500E 25.000N	5.5000E 9.000N	2018 × 1794
	Niger	0.000E 24.000N	16.000E 11.000N	1794 × 1458
	Senegal_Mauritanie_ Gambie_Guinée	-18.000E 27.375N	-4.500E 10.000N	1514 × 1948
Central Africa	Centre_Afrique	13.000E 24.000N	39.000E 2.000N	2914 × 2466
	Soudan	21.000E 24.000N	39.000E 3.000N	2018 × 2354
	Tchad_ RepCentreAfrique	13.000E 24.000N	28.000E 2.000N	1682 × 2466
East Africa	Est_Afrique	28.000E 18.000N	52.000E -5.000N	2689 × 2578
	Erythree_Ethiopie	32.000E 18.000N	48.000E 3.000N	1794 × 1682
	Ouganda_Kenya	29.000E 5.000N	42.000E -5.000N	1458 × 1122
	Rwanda_Burundi	28.000E -1.000N	31.000E -5.000N	338 × 450
	Somalie	40.000E 12.000N	52.000E -2.000N	1345 × 1570

For the current year, the anomaly is calculated using the available decades from the start of the growing period (start decade chosen by the user). To obtain significant anomaly values, the calculation only starts when a minimum of 15 percent of the mean productivity has already been produced. Otherwise, the pixel is given a flag value of 251 which means the growing period is not advanced enough to give significant and reliable anomaly values.

Overlay process

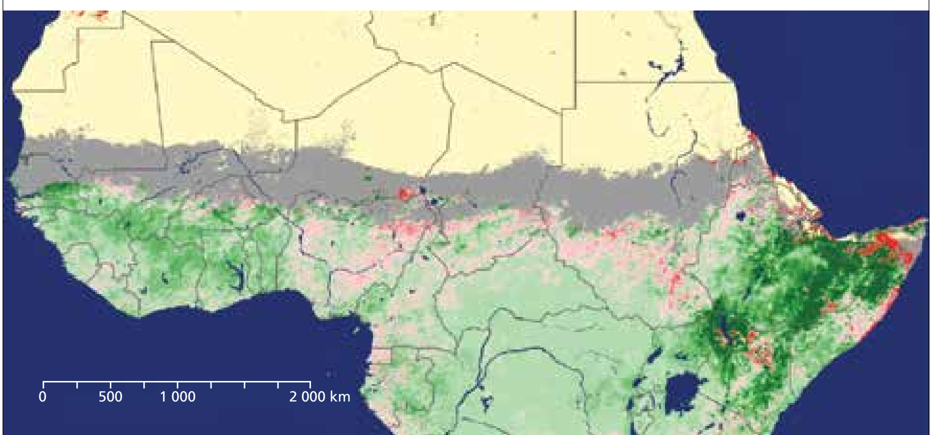
As stated earlier, biomass production monitoring is essential but not sufficient to obtain a proper feed inventory. Accessibility to forage, distance from water points and livestock

FIGURE 10.3
Biomass map [kg.ha^{-1}] in 2010 calculated in July 2010 (last decade)



Pas de biomasse	151 - 300	751 - 1 000	2 001 - 2 500
1 - 50	301 - 500	1 001 - 1 500	2 501 - 3 000
51 - 150	501 - 750	1 501 - 2 000	3 001 - 5 000
			> 5 000

FIGURE 10.4
Biomass anomaly map (percent) of 2010 calculated at the end of July (last decade 2010)



0 - 20	61 - 80	121 - 140	181 - 200
21 - 40	81 - 100	141 - 160	Pas de biomasse
41 - 60	101 - 120	161 - 180	Saison pas commencée

behaviour are additional factors which must be considered. As shown in Figure 10.5, it is possible to achieve higher levels of accuracy by adding layers and improving the quality of each of these.

Surface water monitoring

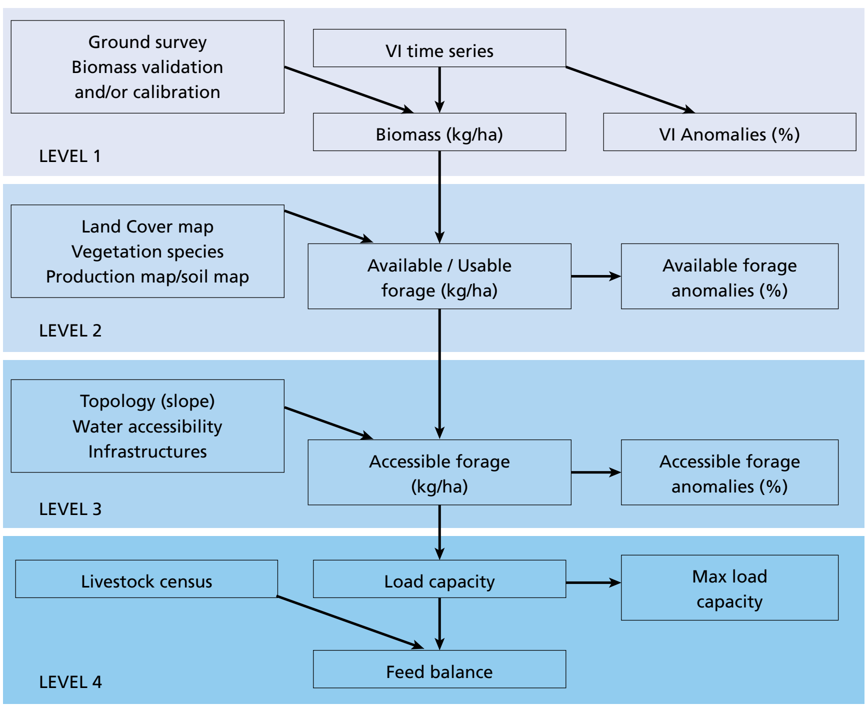
The *Hydrogenerator*, developed between 2009 and 2010 by ACF, considers surface water bodies and their evolution throughout the year. The tool realizes a decadal sum of detected cells and represents a cumulative surface water detection map for the period between 2000 and today. For one given year, the tool also products a surface water accessibility map which helps to characterize the zones considering the water residence time and their influence on a 30 km buffer ring around the detected cells.

This tool is available, but needs some additional ground truth work to be validated. Other tools and systems are also in development and could complement ACF systems (see **References** for existing studies).

Wells and boreholes database

Mapping out boreholes and wells can greatly complement the surface water monitoring process. Given that some areas rely heavily on surface water for livestock needs, some others are more dependent on underground water availability. An updated database available can assist in distinguishing areas that can be used for livestock feed.

FIGURE 10.5
Feed balance diagram



Concentration area mapping

Pastoral movements and concentration areas may largely vary considering the available resources. However, "usual" movements can be determined and compared with the effective movements of the considered year in order to obtain a better understanding of the possible adaptive strategies of breeders and also to be able to anticipate the difficulties people could face some time later. Analysing these patterns is important in the framework of feed inventory updating.

Topography

In hilly areas, some forage areas are not accessible and should not be taken into the feed inventory calculation. Overlaying a Digital Elevation Model can eliminate forage that is inaccessible to livestock from the feed inventory calculation.

Livestock census

A reliable livestock census plays an important role in the calculation of livestock feed balance as shown in Figure 10.5.

10.4 UPDATING THE INVENTORY

Every year, at the end of the rainy season, the feed inventory is updated, combining biomass and surface water maps as well as other data layers. Ongoing monitoring of cattle movements, concentration areas and livestock numbers is useful for identifying potentially vulnerable areas. All these elements comprise the basis for a basic feed inventory, but additional data and information would be useful to produce a fully reliable feed inventory, as shown in Figure 10.5. Higher levels of accuracy will be attained by utilizing additional data, provided they are available.

ACF International intends to further develop the system and distribute it to other countries in West Africa as well as East Africa. Improvements could lead, in time, to the development of an African pastoral vulnerability model.

10.5 REFERENCES

Baret, F., Weiss, M., Lacaze, R., Camacho, F. & Smets, B. 2011. Global long time series of LAI and FAPAR essential climate variables from the capitalization of current existing products: principles and validation of GEOV1 products. *EARSel Symposium*.

Combal, B., Haas, E. & Bartholome, E. 2009. *Detection of surface water with spot/vegetation. Monitoring and assessing CILSS countries surface water availability*. Joint Research Centre, European Commission.

Combal, B., Haas, E. & Bartholome, E. 2009. *Operational monitoring of water bodies in arid and semiarid regions with SPOT/VEGETATION satellite: Contribution of EUMETCAST and recent research projects*. Joint Research Centre, European Commission.

D'Andrimont, R., Pekel, J.-F. & Defourny, P. 2010. *Monitoring water bodies over whole Africa at 250 m resolution: multi-annual analysis of various spatio-temporal dynamics*. Unpublished Poster. Department of Environmental Sciences and Land Use Planning, Université Catholique de Louvain, Belgium.

Fillol, E. & Metais, T. 2008. *Evaluation des risques liés aux variations spatiotemporelles de la pluviométrie au Sahel. Bastide*. XIVth IWRA World Water Congress, Montpellier. Action Contre la Faim.

Fillol, E., Metais, T. & Gomez, A. 2008. *Using remote sensing to estimate the quantity of biomass in the Mali-Niger Sahel region to assist in the management of pastoral activities*. Action Contre la Faim – Internal report.

Haas, E., Bartholome, E. & Combal, B. 2006. *A map of temporary water bodies in Western Africa*. Joint Research Centre, European Commission.

Haas E., Bartholome, E. & Combal, B. 2009. *Time series analysis of optical remote-sensing data for the mapping of temporary surface water bodies in Sub-Saharan Western Africa*. Joint Research Centre, European Commission, Journal of Hydrology.

Haas E. 2010. *Temporary water bodies as ecological indicators in West African drylands*, Joint Research Centre, European Commission, UCL and IES.

Ham, F., Metais, T., Hoorelbeke, P., Fillol, E. & Crahay, P. 2011. One horn of the cow: an innovative GIS-based surveillance and early warning system pastoral areas of Sahel Action Contre le Faim, *In*: Risk returns, pp.127–131, United Nations International Strategy for Disaster Reduction Secretariat (UNISDR) Publishers, Leicester, United Kingdom.

Macopiyo, L.A. 2005. *Spatially explicit, individual-based modelling of pastoralists' mobility in the rangelands of East Africa.* Texas A&M University, USA.

Metais, T. 2007. Suivi des paturages au Sahel. *SPOT Magazin*. No. 42. Action Contre la Faim.

Otto Naes, L., Sullivan, M., Khinmaung, J., Crahay, P. & Otzelberger A. 2010. *Changing climate changing lives, adaptation strategies of pastoral and agro-pastoral communities in Ethiopia and Mali.* Action Contre la Faim, Tearfund, and IDS.

Senay, G., Whisenant, S., Asante, K., Angerer, J., Huckett, S., Singh, R., Manohar Velpuri, N. & Alemu H. 2010. *Enhancing the Livestock Early Warning System (LEWS) with NASA earth-sun science data, GPS and RANET technologies*. Enhanced LEWS DSS – Benchmark Report. NASA. Texas A&M University, USA.

Smets, B., Eerens, H., Jacobs, T. & Royer A. 2007. Towards an operational GMES land monitoring core service. BioPar dry matter productivity from SPOT VEGETATION data. *VITO Geoland,* 2.

11. Development and application of Earth observation-based rangeland monitoring techniques in Namibia

Christophe Sannier
Systèmes d'Information à Référence Spatiale (SIRS), Parc de la Cimaise I, 27 rue du Carrousel,
59650 Villeneuve d'Ascq, France
Email: christophe.sannier@sirs-fr.com

11.1 INTRODUCTION

A significant proportion of the Southern African population is dependent on livestock as a source of revenue and food, and most Southern African livestock rely exclusively on rangeland for fodder. Therefore, the monitoring of rangeland is an essential factor in assessing food security. In addition, because of the high spatial and temporal variability of vegetation growth in most parts of the region, it is essential to monitor rangeland vegetation at regular intervals during the growing season over large areas in order to provide real-time estimates of vegetation conditions. Remotely-sensed data is therefore particularly relevant.

Within the context of setting up a national feed assessment for rangeland vegetation, several approaches can be implemented which can complement each other. Ideally, this would form a series of steps with increasing degrees of precision in terms of available fodder quantity and quality estimates. Within the scope of this case study, this process can be undertaken in two separate steps:

- The initial step is the provision of satellite-derived data products of vegetation conditions over an entire country on a regular basis. This is presented in Step 1 below. The advantage of this approach is that it requires little or no calibration data and can provide regular estimates throughout a growing season. This approach has been applied in several Southern African countries and is now being applied operationally for the whole of Africa.
- A second step involves a more quantitative approach to estimate net primary production from the integration of field measurements with satellite imagery. These estimates can be linked to fodder availability. This approach is presented in Step 2 below. Although the example is for the Etosha National Park in Namibia, the method could be applied over a whole country.
- In a third step, not detailed here, national estimates could be derived by developing estimates for individual land use/cover types, such as agro-ecological/farming systems. These estimates could then be applied to a national land use/cover map. Land use/cover maps would normally be derived from remote-sensing data, or provided by government agencies.

11.2 STEP 1: REAL-TIME RANGELAND MONITORING WITH NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION - ADVANCED VERY HIGH RESOLUTION RADIOMETER (NOAA-AVHRR)

11.2.1 Introduction

Namibia is a dry semi-arid country located in southwestern Africa with a total area of 825 000 km^2. The population is just over two million but is increasing rapidly. Most of the country's climate is arid to semi-arid with a mean annual rainfall varying between almost 0 mm on the coastal desert up to 600 mm in the northeast. The rainfall is highly variable, both spatially and temporally. Only 1 percent of the country's land is fit for agriculture, although population pressure is forcing increases in agriculture into less suitable areas. The rest of the land is mostly occupied by rangeland and desert. The country's largest source of income after mining is cattle.

In the past two decades, the country has been hit by a number of droughts and the combination of low rainfall years and an increase in the animal population have led to overgrazing and ultimately land degradation in the most affected areas. However, it is difficult to say whether the situation has become irreversible or whether it will improve as soon as the rains return to normal. This situation has led government and donor agencies to seek better ways to monitor the current rangeland vegetation conditions in order to make better management decisions.

Previous studies (Hutchinson, 1991; Lambin *et al.*, 1993), have shown the advantage of satellite remote sensing, particularly NOAA-AVHRR, for the monitoring of vegetation conditions compared with methods based on rainfall data interpolation. In the case of Namibia, the available network of rain gauges is not sufficient to allow a reliable interpolation of spatial variation in annual rainfall over the whole country. The most widely used satellite-derived indicator of vegetation activity is the NDVI (Normalized Difference Vegetation Index).

There is a need to compare the current NDVI with historical data in order to assess whether vegetation conditions are better or poorer than usual and in the latter case to know if conditions are sufficiently extreme to adversely affect livestock and crops. Major international initiatives (USAID-FEWS[8], FAO) were set up to develop operational early warning systems which compare current NDVI images with the previous 10-day period or with the mean image for the 10-day period being considered (e.g. first 10 days of June for all years of data) (Hutchinson, 1991; Lambin *et al.,* 1993). The latter method assumes the annual variation of the NDVI for a location and a given 10-day period to follow a Gaussian distribution. This assumption is unreasonable because the lower limit of the NDVI is truncated by the response for bare soil. An improved method developed and tested by Sannier *et al.* (1998) in Namibia and Zambia, estimates the statistical distribution from the NDVI time-series by applying techniques commonly used in hydrology for the prediction of extreme events and defines a Vegetation Productivity Indicator (VPI). This section describes how this methodology was developed and adapted for the Namibia Early Warning System (EWS) at the Department of Meteorological Services and the Ministry of Agriculture of Namibia through the Northern Namibia Environmental Project.

[8] Famine Early Warning System

11.2.2 Implementation of real-time vegetation monitoring in Namibia

Real-time vegetation monitoring with satellite imagery is only possible if reliable local reception of satellite data is available. Over the last decade, the LARST (Local Application of Remote Sensing Technology) consortium led by the Natural Resources Institute (NRI) has developed low-cost satellite receivers capable of acquiring NOAA-HRPT (High Resolution Picture Transmission) data. The system comprises an antenna and a receiver connected to a PC with the appropriate capture card and software. One such system was installed at the Etosha Ecological Institute in Okaukuejo where NOAA-AVHRR data are acquired and used for production of NDVI images on a daily basis.

The ARTEMIS[9] NDVI archive that was used previously covered the 1981–91 period. There was a need to extend this period to improve the implementation of the VPI method. The NASA-GSFC (National Aeronautics and Space Administration - Goddard Space Flight Centre) Pathfinder AVHRR Land (PAL) data set was available up to September 1994. Additional data were also available on the ADDS (Africa Data Dissemination Services) internet site of the USGS which were processed the same way as the ARTEMIS data for the period starting August 1995 up to present (the data are being continuously updated). The combined data set covers a 15-year period.

The ARTEMIS and PAL archives were compared by Sannier *et al.* (1998) in the overlap period and showed that although there was a strong relationship between ARTEMIS and PAL NDVI values, they were significantly different. However, the PAL archive NDVI values for the 1991-94 period were matched to the ARTEMIS values using a regression relationship. Comparison of the ADDS data with ARTEMIS values over stable targets such as deserts showed that the values were directly compatible with ARTEMIS. An 18-year time series of 10-day maximum value composite NDVI images for Namibia and its surroundings was extracted from the various data sources identified in Table 11.1.

The ISODATA algorithm (ERDAS, 1995) was used to perform several unsupervised maximum likelihood classifications on the thirty-six 18-year mean 10-day images, varying clustering parameters and the number of classes. Cloudy pixels were eliminated in the calculation of the 18-year averages. Finally, a 14-class classification was selected to stratify the study area for the VPI method. The NDVI statistical distribution for each 10-day period and each stratum was determined using the method described by Sannier (1998). This was to determine the NDVI values corresponding to quintile probability thresholds used to define five vegetation status classes (very low, low, average, high and very high) in each stratum as shown in Figure 11.1. Figure 11.2 shows these thresholds plotted against time for two locations.

11.2.3 Development of outputs

The methodology was commissioned in the Ministry of Agriculture and the Ministry of Environment and Tourism and a workshop was held in Windhoek to discuss the format and dissemination pathways for outputs including maps, graphs and tabulated statistics. A map for reporting at ministerial level during the rainy season was identified. This consisted of the maximum VPI value obtained from three 10-day periods, was simple to implement and was thought to further remove cloudy pixels. An example of a monthly VPI map is shown in Figure 11.1.

[9] Advanced Research & Technology for Embedded Intelligence and Systems.

TABLE 11.1
Data sources for the 18-year Namibia data set

Time Period	Data Source
1st 10-day period August 1981 to 3rd 10-day period June 1991	FAO-ARTEMIS
1st 10-day period July 1991 to third 10-day period July 1994	NASA/GSFC PAL
1st 10-day period July 1995 to third 10-day period June 1997	USGS/FEWS/ADDS

The VPI maps show the spatial distribution of rangeland vegetation conditions for the whole of Namibia at a particular moment in time. It was also considered important to monitor vegetation condition at a single location over time by plotting the current NDVI on the vegetation status profiles such as the one shown in Figure 11.2. This supplements the information from the maps and assists the production of seasonal forecasts. Macros were developed to enable timely production of these plots for six main locations in the country (Gaborone, Kasane, Francistown, Maun, Guanzi and Tsabong). In the Kalahari (Figure 11.2a) the vegetation response was both exceptionally early and exceptionally high whereas in Mashare (Figure 11.2b) the growing season was two months later than usual and was still low at the time of the last image plotted. DMS and Ministry of Agriculture staff were shown these methods and were trained to produce similar graphs.

FIGURE 11.1
VPI map of Namibia for October 1999

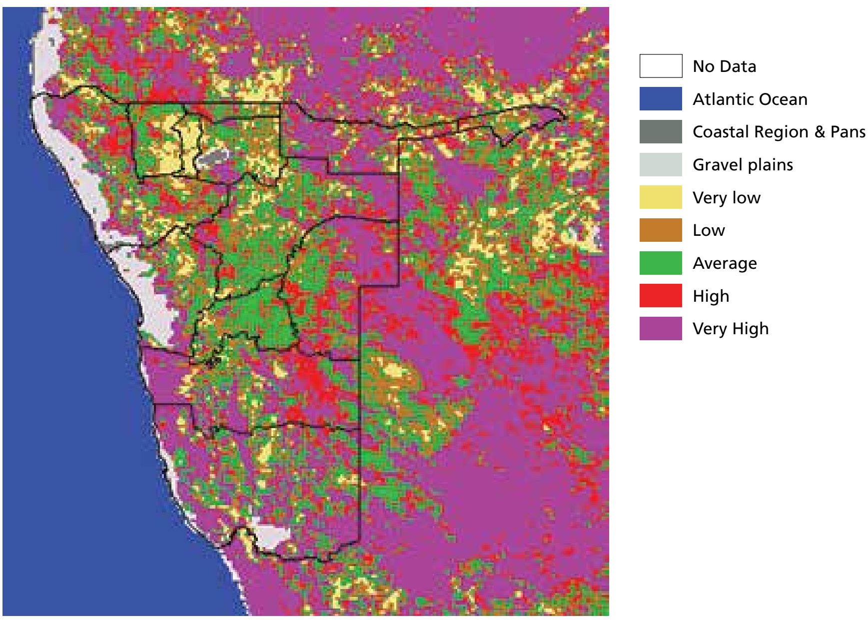
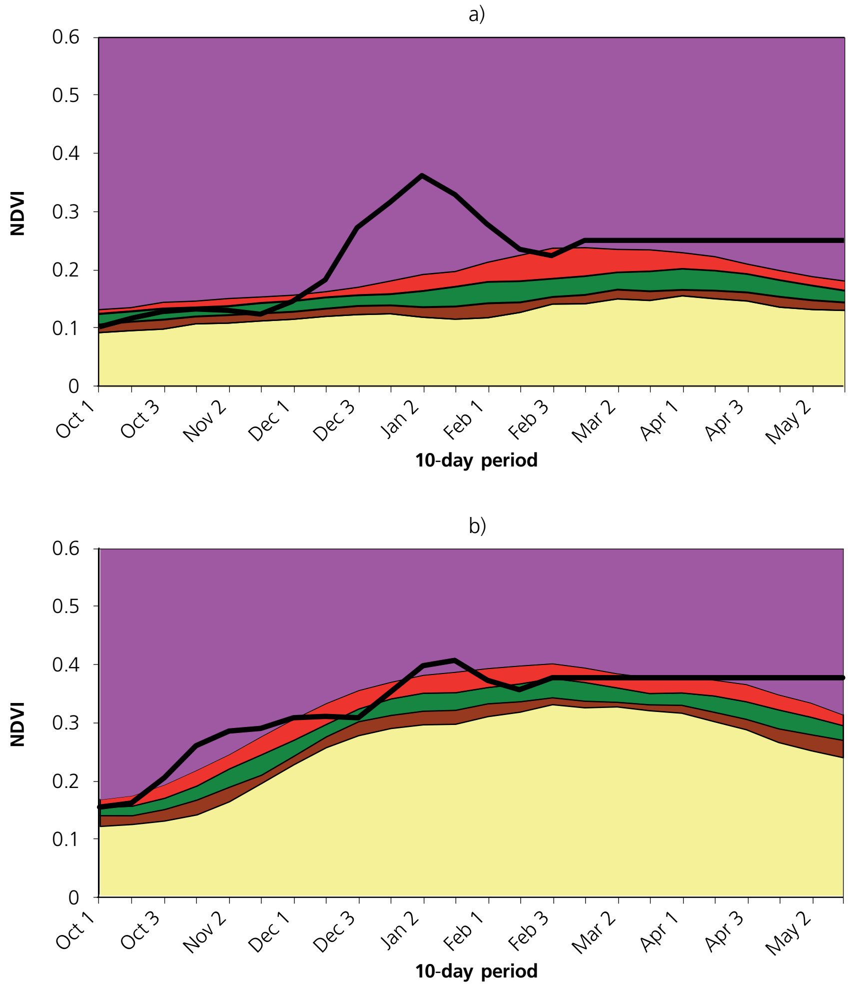


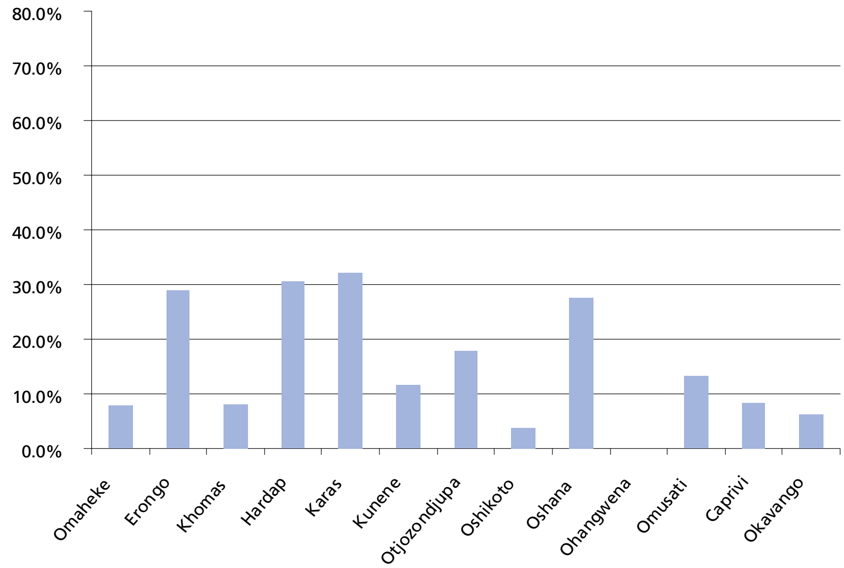
FIGURE 11.2
Evolution of vegetation conditions
(a) in Kalahari and (b) in Mashare, Namibia, during the 1998-99 season



Note: Colours in graphs represent VPI categories listed in Figure 11.1. Solid black line indicates current year vegetation condition.

There was also a need for a simple output to indicate conditions at the level of agricultural districts. The number of pixels below average conditions for each district was imported into a pre-formatted spreadsheet to produce a graph (Figure 11.3) of the percentage of each district suffering from potential drought conditions. This information contributes to the rapid identification of districts with problems.

FIGURE 11.3
Proportion of agricultural districts of Namibia below average in March 1999



11.2.4 Dissemination and field checking of outputs

Workshops and training seminars were held with Ministry of Agriculture and Ministry of Environment and Tourism staff. Presentations and interpretations of the VPI maps were given to the members of the Namibia EWS to raise awareness of the new information described above and to provide training in its use. This is an ongoing process that will be expanded to include users at a district level, in order to increase the use and impact of the products. The VPI maps and associated products have also been distributed to a wide range of general users in Namibia through 10-day and monthly agro-meteorology bulletins produced by the Ministry of Agriculture. The VPI maps are used to monitor potential drought conditions and to provide a visual summary of the current status of Namibia's rangelands.

National drought assessment tours are conducted by multidisciplinary teams at least twice a year to assess drought conditions on the ground. The VPI maps can be used to target visits to worst-hit areas and to assess the spatial extent of conditions that are identified in the field.

11.2.5 Conclusions

The implementation of the VPI methodology in Namibia seems to have worked extremely well and VPI maps are now being produced operationally and can be distributed to the relevant authorities. Initial field checking by NNEP staff also showed that VPI products were effectively picking up variations in vegetation development compared with the norm. The use of the VPI maps for drought monitoring has made a significant contribution to the identification of drought severity, the spatial extent of the area affected, and the drought relief measures to be introduced. VPI maps are now being used by range managers in Namibia as a monitoring tool.

11.3 STEP 2: COMBINATION OF FIELD DATA AND SATELLITE OBSERVATION FOR NEAR REAL-TIME MONITORING OF RANGELAND VEGETATION IN ETOSHA NATIONAL PARK

One of the key biophysical variables that is measured in assessments of rangeland vegetation conditions is biomass production or net primary production. Biomass observations can be collected in the field, but field methods are only suitable to cover a small area and are too costly and time consuming for real-time monitoring over large areas. On the other hand, satellite imagery can cover large areas on a daily basis using low spatial resolution satellite imagery. However, satellite imagery on its own can only provide qualitative estimates of biomass. Quantitative estimates derived from satellite imagery can only be achieved if images are calibrated with appropriate field observations.

This section presents a methodology relying on the combination of medium to low spatial resolution satellite imagery and detailed representative field observations of biomass. The objective is the provision of near real-time maps of biomass estimates.

The methodology was developed in the Etosha National Park in the northern part of Namibia. Etosha covers an area of approximately 23 000 km². The climate is semi-arid with a rainfall gradient varying from about 450 mm in the east to 300 mm in the west (Le Roux *et al.*, 1988). The main feature of the Park is the Etosha pan, a saline desert covering an area of approximately 5,000 km^2. Very little or no vegetation grows on the pan, which is sometimes covered with a thin water layer during the rainy season.

The work was carried out in four separate stages: rapid measurements of plant biomass, selection of biomass sites, site sampling strategy and processing of satellite observations. These stages are summarized below, but a more detailed discussion of the methodology is presented by Sannier *et al.* (2002).

11.3.1 Rapid measurement of plant biomass

Rapidity is required primarily for economic reasons (more observations can be collected with the same resources). A second reason is that vegetation growth is limited by rainfall, it develops very rapidly following rainfall events, and it is also consumed rapidly by livestock. Because the intention was to make the biomass observations coincide with satellite imagery, it was essential to derive field biomass estimates as close to the image acquisition date as possible. To estimate the total green biomass per unit area, it was necessary to calculate contributions from herbaceous and woody components at the scale of the pixels. This was done using a statistical estimator based on sample observations.

Herbaceous Biomass

The use of a rising plate or disc pasture meter (DPM) for estimating grass biomass in Australian pastures was first described by Mitchell (1982). It has the advantage of being objective, rapid and easy to operate and was adopted for herbaceous biomass assessment in this work. However, judgement is required when making measurements on stony ground to avoid false readings.

Previous work in Etosha by Kannenberg (1995) produced a calibration curve in using the same calibration procedure as Trollope and Potgieter (1986). The curve includes points from a wide range of locations and the single curve seems to be generally applicable for all Etosha grasses. The linear model for the regression produced a high coefficient of determination (r^2) but the scatter of points for biomass below 2000 kg/ha seems to deviate systematically below the regression line with a risk of overestimating biomass below this threshold. An alternative logarithmic model shown in Figure 11.4, and proposed for this work, is an improvement and has a higher r^2.

Woody plant biomass

Green biomass estimation of woody plants is usually estimated by using a regression relationship between dry matter weight obtained from direct harvest and a plant morphological variable such as height, stem diameter or crown diameter (Pieper, 1988). The dominant woody species in Etosha, accounting for about 85 percent of the shrubs and trees in the savanna, is mopane (*Colophospermum mopane*) which occurs in both forms. Data relating the branch diameter of mopane to leaf biomass was available from previous work at the Etosha Ecological Institute (Du Plessis, 1995). This was used to create a rapid field technique to estimate the biomass of mopane trees and shrubs. Table 11.2 shows the average leaf biomass of mopane for stems and branches in different size categories. The leaf biomass of a randomly selected sample of 80 mopane trees and shrubs was estimated in the field by counting the number of primary stems in each of the size categories and using the average leaf weights from the table. The height of the plant and its crown diameter in two perpendicular directions was also recorded. The estimated dry leaf weight was best correlated to the volume of the plant calculated as a cylinder with diameter equal to the average crown size and height equal to the estimated tree height as shown in Figure 11.5.

FIGURE 11.4
Estimation of grass biomass with the Disc Pasture Meter

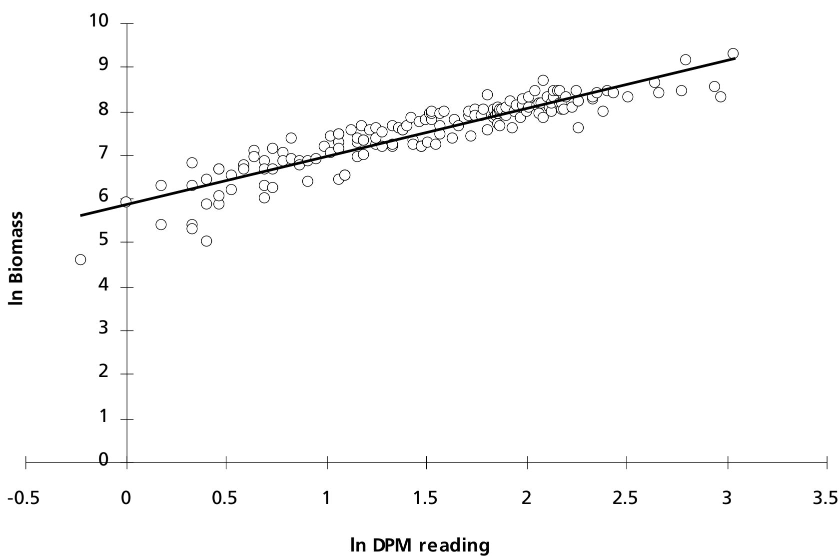
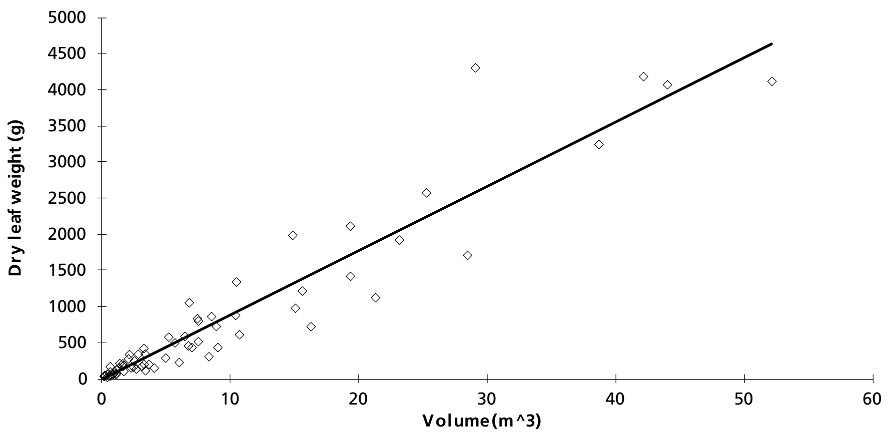


TABLE 11.2
Average leaf weight of mopane stems in full leaf, in different size ranges

Stem Diameter class (cm)	Average leaf dry weight (g)	Standard Error (g)
0 to 0.5	1.6	0.1
0.5 to 1	6.9	0.4
1 to 2	28.3	1.8
2 to 3	84.8	8.2
3 to 4	171.2	11.3
4 to 5	239.7	26.4
5 to 6	387.2	81.3
6 to 7		
7 to 8	785.2	83.6
8 to 10	1240.7	209.6
10 to 12	1595.0	223.9
12 to 14	1714.8	190.3
14 to 16	2683.0	216.6
21 to 28	2883.2	774.0

The dominant shrub in Etosha steppe areas is leucosphaera (*Leucosphaera bainesii*), accounting for around 80 percent of steppe shrubs. Unlike mopane, no previous work on the assessment of plant biomass had been done on leucosphaera. Seventy-two plants were randomly selected in the field; height and perpendicular crown diameters were measured, then the plants were harvested. Total dry plant weight was determined following standard

FIGURE 11.5
Calibration of shrub and tree green biomass with crown volume



oven drying. The total dry plant weight was considered more appropriate to use because the plants almost completely disappear during the dry season, therefore any plant material above the ground was considered new material. The best relationship between dry plant biomass and plant dimensions was found using crown area and is shown in Figure 11.6. Unlike mopane, plant volume was not the best correlate to biomass because leucosphaera is a smaller plant which develops itself horizontally rather than vertically.

11.3.2 Selection of biomass sites

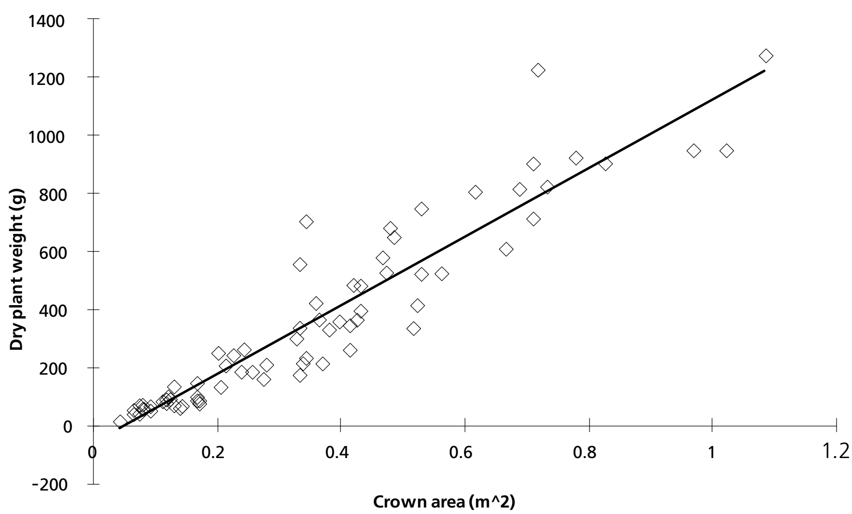
The criteria for selecting calibration sites were that they:

- be of sufficient size and internally homogeneous to reduce the effects of errors in co-location of the ground with satellite observations;
- be accessible; and
- reflect the range of biomass levels in the Park.

Sites were chosen to reflect the variation of the predominant grass, steppe and savanna types in the Park.

The formula derived by Justice and Townshend (1981) gives a guideline for the minimum size, *a*, of a sampling unit in relation to the geometric accuracy: $a = p(1+2l)$ where *p* is pixel dimensions in distance units and *l* the geometric accuracy in number of pixels. For example, a 1.1 km pixel size for NOAA-AVHRR and a geometric accuracy of 0.5 km pixel should result in a sampling unit of 2.2 km on each side. Generally, it is not feasible to have calibration sites large enough to meet this ideal and in past studies smaller sites have been used. We initially selected candidate homogeneous locations, several square km in size by photo-interpretation of geometrically corrected false colour composites from Landsat TM imagery. By selecting a 1 km^2 site in the middle of a larger homogeneous area, we expected to minimize the effects of geometric correction errors. This is because

FIGURE 11.6
Calibration of dwarf shrubs with plant crown area



variation of biomass in the immediate surrounding area was unlikely to be great and also because surrounding pixels would not be mixtures of other vegetation types. Field checking with geo-coded enlargements of the TM imagery verified the homogeneity of the selected sites. A total of 11 sites were selected as shown in Figure 11.7.

11.3.3 Site sampling strategy

Biomass sampling was carried out along a 1 km transect through the centre of the 1 km^2 sample site. Because of our previous selection procedure, it was assumed that the site is isotropic and homogeneous so that average biomass along the transect represents the average for the whole of the 1 km square area. The sampling scheme for herbaceous vegetation is shown in Figure 11.8. DPM measurements were made at ten equally spaced locations along the transect. Navigation was assisted by a Landsat TM enhanced geo-coded image hardcopy and a handheld GPS. Five clustered DPM readings were taken on each side of the transect. This resulted in a total of 100 DPM measurements per site which is the value suggested by Trollope and Potgieter (1986).

The woody plant biomass per unit area is the product of the biomass per plant and the number of plants per unit area. The number of plants per unit area is estimated by dividing proportion of plant cover (canopy area/unit ground area) by the canopy area per plant. The crown to gap method (Westfall and Panagos, 1984; Walker *et al.,* 1988) is a very fast and

FIGURE 11.7
Selection of survey sites

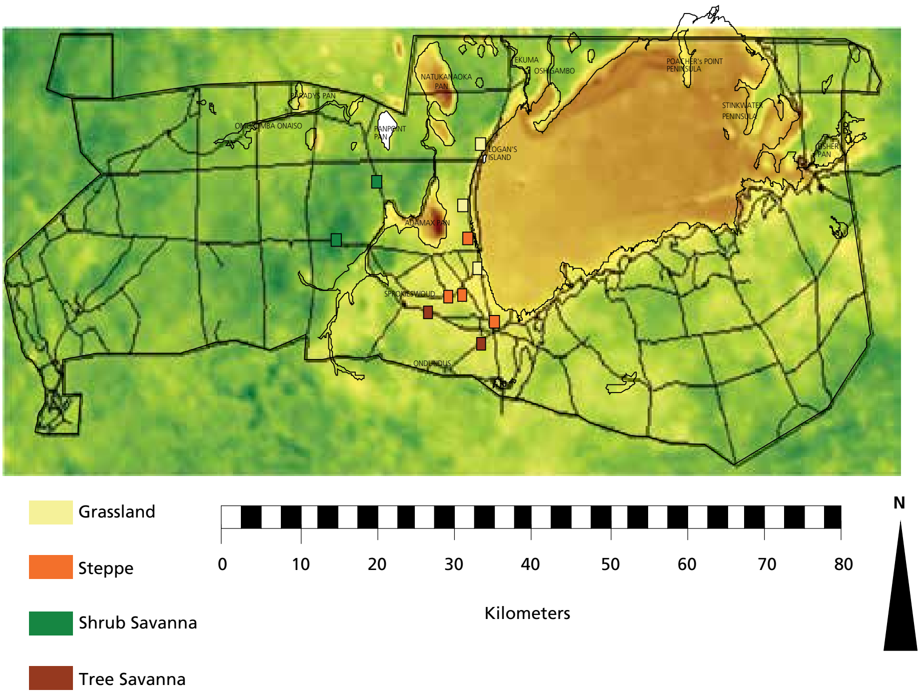
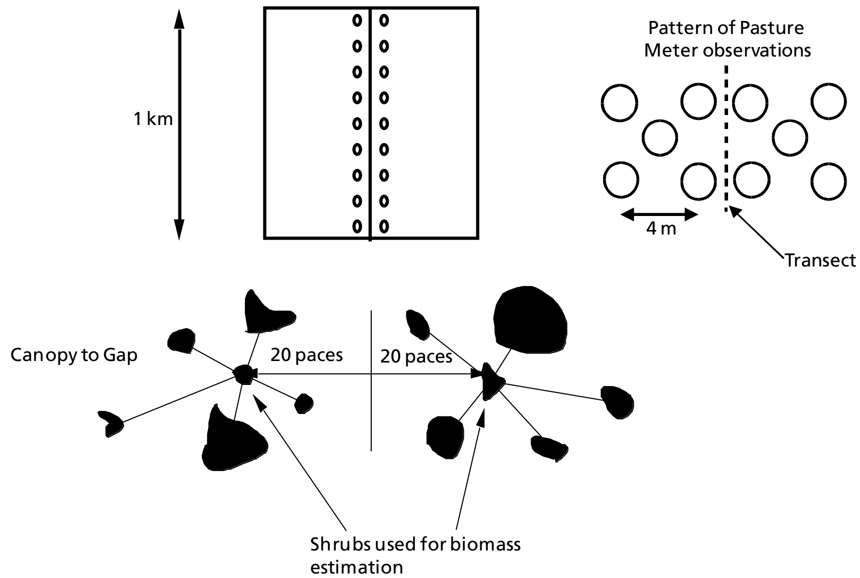


FIGURE 11.8
Sampling strategy for biomass measurements



unbiased method for estimating the percentage canopy cover of woody vegetation (trees, shrubs, dwarf shrubs, etc.) over relatively large areas from ground observations or surrogates such as photographs and was selected for this study. Two adjacent plants approximately the same distance from the observer were selected. The ratio ϕ, the distance between their crowns (*G*) to the diameter of the crown of one of them (*K*) in Equation 1

$$\phi = \frac{G}{K} \qquad (1)$$

can be estimated by eye or by a transparency gauge (Westfall and Panagos 1984) or measured on photographs. The average ratio $\bar{\phi}$, for at least 25 pairs of plants is used in Equation 2, described by Walker *et al.* (1988) to estimate the percentage covered by the crowns, *C*:

$$C = \frac{100\pi}{2\sqrt{3}} \left[\frac{1}{\left(\bar{\phi} + 1\right)^2} \right] \qquad (2)$$

The sampling of woody vegetation was done on the same 10 locations along the transect as shown in Figure 11.8. A plant was randomly selected on each side of the transect by walking 20 paces perpendicular to the transect using the vehicle as a reference. Then the closest plant was selected to take plant measurements. The reference plant was also used to perform the canopy to gap procedure as shown in Figure 11.8 by choosing five other plants closest to it and evaluating visually the canopy to gap ratio between the reference plant and each of the five other plants measurement.

The whole procedure was repeated on the other side of the transect. In total, for each site, 100 DPM measurements, 100 canopy-to-gap ratio estimations and 20 plant dimensions were taken.

11.3.4 Determination of site total green biomass

The estimation of herbaceous biomass per site is simple because DPM measurements are directly related to biomass per unit area. DPM readings were recorded in a spreadsheet. Each cluster of five DPM readings (Figure 11.5) was averaged. This was to create observations comparable with the original calibration procedure. The calibration equation was applied to the averaged value resulting in 20 grass biomass value per site. The overall biomass of the site was calculated by taking the mean of the 20 biomass values. The same method was used in woody vegetation sites without taking into account the woody cover because grass also often grew under the trees and shrubs and a reading of zero was recorded when the DPM fell on a shrub.

The estimation of woody biomass includes several parameters and the process of averaging was carefully considered because of non-linearity. Each location along and on each side of the transect was treated individually. This was to take into account all of the variations within the site and the non-linearity of the canopy to gap ratio method. A biomass value was calculated for each of the 20 sampled plants associated with five measurements of density (canopy to gap ratio). These five estimates of density were averaged to establish the density at each plant location. The density combined with the plant area gives the number of plants per unit area. The number of plants per unit area multiplied by the plant weight gives the biomass corresponding to the plant and density considered. Twenty plants and five measurements of density per plant resulted in 100 observations of biomass per site. The estimate of biomass for the whole site was the arithmetic mean of these 100 biomass observations plus the grass biomass.

Biomass per plant, P, in kilogrammes is determined by the relationship between plant dimensions and biomass defined earlier. The density cover, C, is determined according to equation (2). The number of plants per hectare, N, is:

$$N = \frac{10000}{A} \cdot C \qquad (3)$$

Finally, the total woody biomass per hectare and plant, W_i, is equal to:

$$W = P \cdot N \qquad (4)$$

In the case of leucosphaera, the calculation of biomass is simplified because the crown area is used in both the calculation of P and N which are cancelled out. Therefore, for leucosphaera, woody biomass is only related to C and the slope of the calibration between plant biomass and area.

For mopane, where the relationship with biomass is based on volume, woody biomass is a function of the slope of the calibration, height and C. It means that once the relationship between biomass and plant dimensions has been established, it is not required to measure plant area in order to derive estimates of woody biomass. The total woody biomass per site is equal to the average of the 20 estimates derived per plant. The combined grass and woody biomass is obtained by adding the two estimates.

In total, 25 observations of biomass were made for the 11 sites selected over two seasons as shown in Table 11.3.

11.3.5 Processing of satellite imagery

NOAA-AVHRR imagery was used for this work and was acquired in real time from a LARST receiving station (Williams and Rosenberg, 1993). This allowed us to produce NDVI images in near real time, to select only the best images and to make sure that the images would coincide with the fieldwork. A total of seven images was selected. Data processing consisted of radiometric and geometric correction of the imagery and NDVI calculation.

Radiometric corrections were based on the work published by Kaufman and Holben (1993) and Los (1993) for NOAA9 data and Rao and Chen (1996) for NOAA14, which took sensor degradations into account and was later updated monthly on the NOAA web site.

Geometric correction was based on the selection of control points from the geo-referenced Landsat TM mosaic covering the entire Park. This made it possible to achieve a geometric accuracy of about 0.5 pixel, which is much better than could have been achieved using satellite orbital parameters.

No atmospheric or bidirectional effects correction was performed because it was thought that careful selection of imagery, free of clouds and nearest as possible to nadir, would be more efficient in keeping atmospheric effects to a minimum rather than applying an approximate atmospheric correction. Existing methods for removing atmospheric effects often assume constant effects over the entire scene and require ground meteorological data that are not realistic to obtain for near real time application.

Digital number (DN) values were extracted from the imagery for each waveband and for each site. The data were input into a spreadsheet where radiometric corrections and NDVI calculations were carried out. Corresponding biomass values were input in the spreadsheet as shown in Table 11.3 and regression models were developed as shown in Figure 11.9.

The relationship including all observations (Figure 11.9a) was weaker than the relationship including only grassland sites (Figure 11.9b). This seemed to suggest that different regression relationships would have to be developed for each vegetation types. However, insufficient data were available to test this hypothesis on the other cover type, and more data would need to be collected. Nevertheless the pooled relationship (Figure 11.9b) is still highly significant and it was used to produce the biomass maps.

11.3.6 Production and applications of biomass maps

The pooled relationship developed in the previous section (Figure 11.9a) can be used to transform NDVI images acquired at the NOAA HRPT receiving station into biomass maps. There are a number of ways in which these biomass maps can be used. From the point of view of food security, this could include the monitoring of animal movements in relationship to fodder availability during a growing season, or the monitoring of the animal carrying capacity from year to year and throughout a study area.

However, a more direct application of biomass maps is the correlation between fuel loads and fire risks. Fires occur naturally in the Park and are normally triggered by lightning

TABLE 11.3
NOAA-AVHRR biomass calibration results

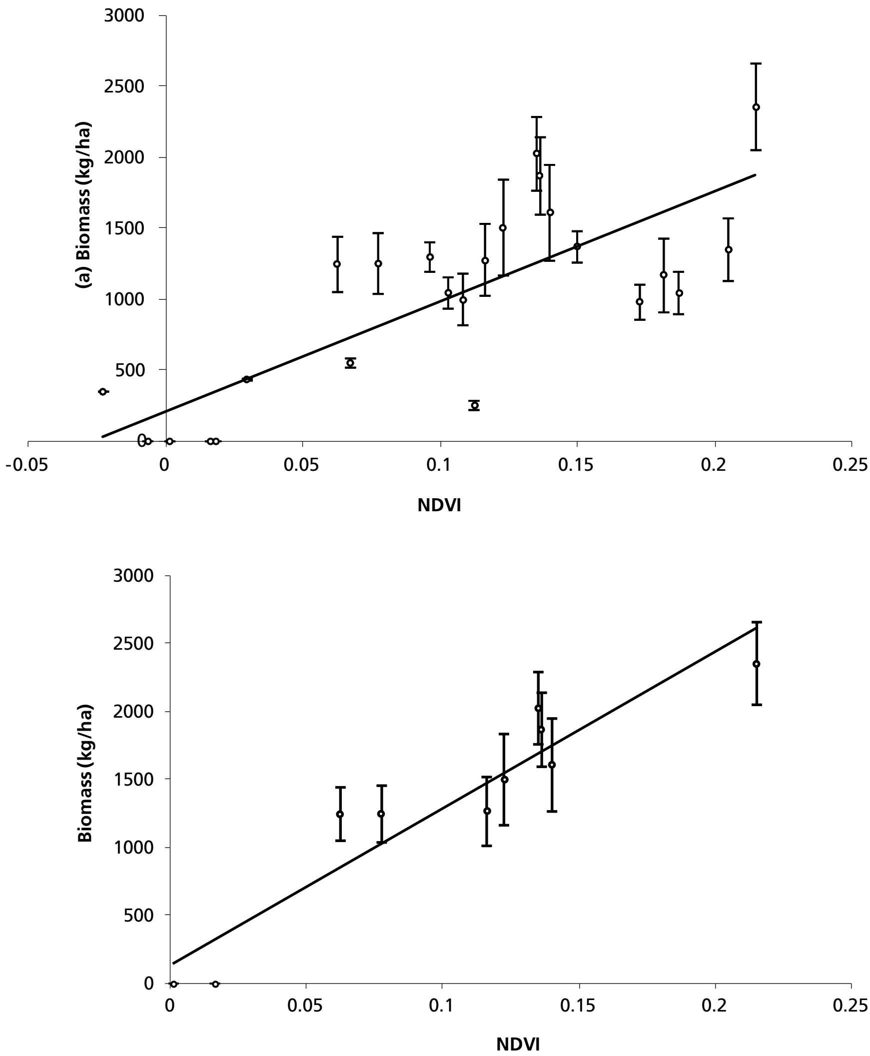
Site	Vegetation Type	Survey date	Image acquisition	NDVI	Biomass (kg/ha)
S4	Grassland	15/02/95	16/01/95	-0.007	0
S6	Grassland	15/02/95	16/01/95	0.001	0
S7	Grassland	15/02/95	16/01/95	0.016	0
S7	Grassland	01/03/95	02/03/95	0.077	1 254
S4	Grassland	01/03/95	02/03/95	0.029	437
S6	Grassland	01/03/95	02/03/95	0.062	1 251
S4	Grassland	10/03/95	10/03/95	-0.023	350
S6	Grassland	21/03/95	21/03/95	0.122	1 506
S7	Grassland	21/03/95	21/03/95	0.135	2 031
S4	Grassland	30/03/95	27/03/95	0.067	553
S6	Grassland	31/03/95	27/03/95	0.140	1 615
S7	Grassland	31/03/95	27/03/95	0.136	1 874
S4	Grassland	25/03/96	19/03/96	0.112	254
S6	Grassland	21/03/96	19/03/96	0.116	1 275
S7	Grassland	25/03/96	19/03/96	0.215	2 357
M1	Savanna	20/03/96	18/03/96	0.187	1 046
M2	Savanna	27/03/96	06/04/99	0.181	1 175
M3	Savanna	28/03/96	06/04/96	0.150	1 375
M4	Savanna	03/04/96	06/04/96	0.205	1 352
S1	Steppe	15/02/95	16/01/95	0.018	0
S3	Steppe	15/02/95	16/01/95	0.016	0
S1	Steppe	26/03/96	19/03/96	0.172	985
S2	Steppe	19/03/96	19/03/96	0.103	1 048
S3	Steppe	01/04/96	19/03/96	0.096	1 300
S5	Steppe	02/04/96	19/03/96	0.108	997

(Heady, 1975). Under favourable conditions, wildfires can spread over large areas and can cause major damage to wildlife and vegetation. However, controlled or prescribed burning is often used to prevent the occurrence of wildfires by reducing fuel loads. Furthermore, controlled fires may benefit livestock and wildlife through positive effects on vegetation regeneration and habitat diversity (Heady, 1975; Holechek *et al.,* 1995). Controlled fires have been used in Etosha National Park for the above reasons and the Park was divided into a number of fire blocks as shown in Figure 11.10.

Trollope and Potgieter (1986) have shown that in the Kruger National Park, biomass fuel loads needed to reach at least 1500 kg/ha to propagate. Therefore, it is possible to use biomass maps reclassified according to a series of thresholds indicating the levels of fire risk. This is illustrated in Figure 11.10, where biomass maps were produced at the end of the

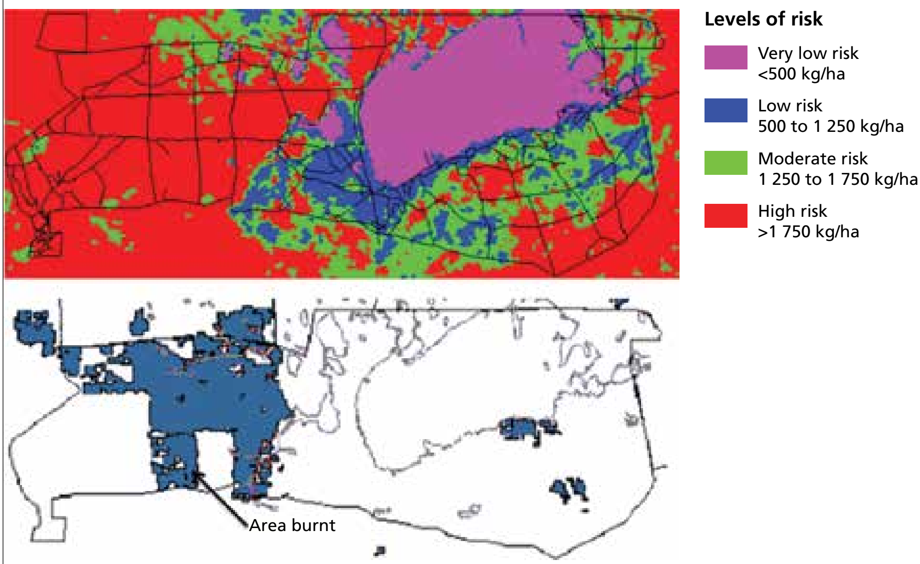
FIGURE 11.9

Relationship between NDVI and biomass for (a) all sites, *n* = 25, *y* = 7735× + 208, r^2 = 0.61 (*p* <0.01) and (b) all grassland sites, *n* = 10 r^2 = 0.89



Note: Error bars represent the standard deviation of the field biomass estimate.

FIGURE 11.10
Example of a biomass map used to estimate fire risk level, and the extent of the fire that occurred two years after



rainy season for 1995, 1996 and 1997 using the pooled NDVI/biomass regression relationship shown in Figure 11.9a. Looking especially at 1995 and 1996, it is apparent how, for controlled burning, such maps could be used to target fire blocks corresponding to the high to very high risk classes. The year 1997 was exceptional, with rainfall in excess of 40–60 percent of the median between 1981 and 1996, which explains the extremely high levels of biomass reached throughout the park. As a result, all the conditions for an extensive fire were met and a wildfire started at the end of the dry season, which burnt nearly 21 percent of the park's area outside the pans, crossing several fire breaks. The conditions of 1997 were very unusual, but it is possible that, had some controlled burning taken place in fire blocks where biomass was already relatively high in previous seasons, the wildfire that took place in 1997 would not have spread so extensively.

11.3.7 Conclusion and further development

This study has demonstrated methods for near real time monitoring of biomass quantity with NOAA-AVHRR. The value and reliability of the DPM has been demonstrated and was shown to be suitable for measuring biomass of grasslands across large areas. However, its use should really be limited to the grass types for which it has been calibrated. It is possible, in certain circumstances, that several calibration curves might be required depending on the grass types present. The DPM is unsuitable for reliably measuring biomass below 1000 kg/ha and other techniques, such as visual estimation, should be used.

Concerning woody plant biomass, the set of techniques that were developed appeared to be reasonably reliable. The calibration of green plant biomass based on dimensions worked particularly well. The canopy to gap method was also very rapid to implement and seemed to be a fairly reliable way to assess canopy cover. Once the calibration of plant biomass with dimensions has been determined, the measurement of woody biomass becomes extremely rapid especially for plant species for which the calibration is based on plant area. In this case, the only parameter required is canopy cover. For plant species in which the calibration is based on volume, the parameters required are the canopy cover and plant height. This makes the assessment of biomass monitoring sites much faster and it is possible to increase the sample size from 20 to 40 plants within a site allowing a better characterization of site variations.

It would also be desirable to extend the work to other plant species, although the existing calibrations that were developed are valid for about 85 percent of the park.

The need to develop a suitable sampling scheme was also identified. The assistance of high resolution imagery for site selection proved to be very useful and allowed the identification of homogeneous sites for selected cover types at the scale of NOAA. It also proved crucial to develop a suitable sampling scheme for the measurement of biomass within the site. The random selection of plants along the transect proved to be particularly important and the measurement of canopy cover needs to be based on the selected plants. This allows measurements of variations within the site and thus assessments of the precision of the estimates.

It was also demonstrated that single AVHRR images, received locally, could be calibrated against biomass allowing near real time monitoring of biomass quantity. Moreover, the methodology could also be applicable to other types of imagery such as SPOT VEGETATION[10] or TERRA/AQUA MODIS[11]. Nevertheless, the number of points available for the calibration is still limited and more observations would be needed to confirm that the calibration remains stable through space and time. It already appears that the same calibration could be used for grassland and steppe. This is particularly encouraging because grassland and steppe are present in the same areas and are difficult to differentiate at the scale of NOAA-AVHRR. However, it seems that savanna sites need a different calibration especially when the proportion of woody biomass reaches a certain level. More observations need to be collected to be able to confirm this theory and to determine this threshold.

Biomass maps could potentially be used for several purposes linked to rangeland and wildlife management such as monitoring of animal movement and assessment of carrying capacity. It was shown that biomass maps could be used for the planning of prescribed burning. If local reception of NOAA-AVHRR data is possible, biomass maps can be produced in near real time and a direct application will be possible to target areas suitable for controlled burning to prevent large-scale wildfires. However, more work is required on refining the relationship between biomass and the NDVI for different vegetation communities, and to investigate whether the effective burning threshold varies according to the

---

[10] The VEGETATION programme is the fruit of space collaboration between various European partners: Belgium, France, Italy, Sweden and the European Commission. In 1998, it was grafted onto the SPOT programme, founded by Belgium, France and Sweden in 1978. It consists of two observation instruments in orbit, VEGETATION 1 and VEGETATION 2, as well as ground infrastructures.

[11] MODIS (or Moderate Resolution Imaging Spectroradiometer) is a key instrument aboard the Terra (EOS AM) and Aqua (EOS PM) satellites.

vegetation type. This latter point stresses the importance of having land cover mapping products as a basis for stratifying the study area.

Finally, although the method was developed over an area of 23 000 km², it could potentially be used over a much larger area, such as nationally, provided a suitable sampling scheme is implemented across the study area.

11.4 REFERENCES

Du Plessis, W. 1995. Biomass calibration of *Colophospermum mopane* in Etosha National Park. Personal communication.

ERDAS. 1995. *ERDAS field guide,* Atlanta: ERDAS Inc., USA.

Heady, H.F. 1975. *Rangeland management*, New York: McGraw Hill, USA.

Holechek, J.L., Pieper, R.D. & Herbel, C.H. 1995. *Range management: Principles and practices* - Second edition, Prentice Hall, New Jersey, USA.

Hutchinson, C.F. 1991. Uses of satellite data for famine early warning in Sub-Saharan Africa. *Int. J. Remote Sens.,* 12: 1405–1421.

Justice, C.O. & Townshend, J.R.G. 1981. Integrating ground data with remote sensing. *In* J.R.G. Townshend, ed. *Terrain Analysis and Remote Sensing.* George Allen & Unwin, London, UK.

Kannenberg, N. 1995. Grass-biomasse in Savannenbiomen des Etosha National Park: Anwendung des Disc Pasture Meter (DPM).

Kaufman, Y.J., & Holben, B.N. 1993. Calibration of the AVHRR visible and near-IR bands by atmospheric scattering, ocean glint and desert reflection. *Int. J. Remote Sens.*, 14: 21–52.

Lambin, E.F., Cashman, P., Moody, A., Parkhurst, B.H., Pax, M.H.,& Schaaf, C.B. 1993. Agricultural production monitoring in the Sahel using remote sensing: Present possibilities and research needs. *J. Environ. Manag.*, 38: 301–322.

Le Roux, C.J.G., Grunow, J.O., Morris, J.W., Bredenkamp, G.J. & Scheepers, J.C. 1988. A classification of the vegetation of the Etosha National Park. *South African J. Botany,* 54: 1–10.

Los, S.O. 1993. Calibration adjustment of the NOAA AVHRR normalised difference vegetation index without recourse to channel 1 and 2 data. *Int. J. Remote Sens.,* 14: 1907–1917.

Mitchell, P. 1982. Value of a rising-plate meter for estimating herbage mass of grazed perennial ryegrass - White clover swards. *Grass Forage Sci.* 37: 81–87.

Pieper, R.D. 1988. Rangeland vegetation productivity and biomass. *In* P.T. Tueller, ed. *Handbook of vegetation science Vol. 14*. *Vegetation science applications for rangeland analysis and management*. Kluwer Academic Publishers, Dordrecht, Germany.

Rao, C.R.N. & Chen, J. 1996. Post-launch calibration of the visible and near-infrared channels of the advanced very high resolution radiometer on the NOAA-14 spacecraft. *Int. J. Remote Sens.,* 17: 2743–2747.

Sannier C.A.D., Taylor J.C., du Plessis W. & Campbell K. 1998. Real-time vegetation monitoring with NOAA-AVHRR in Southern Africa for wildlife management and food security assessment. *Int. J.Remote Sens.*, 19: 621–639.

Sannier C.A.D., Taylor J.C. & du Plessis W. 2002. Real-time monitoring of vegetation biomass with NOAA-AVHRR in Etosha National Park, Namibia, for fire risk assessment. *Int. J.Remote Sens.*, 23: 71–89.

Trollope, W.S.W. & Potgieter, A.L.F. 1986. Estimating grass fuel loads with a disc pasture meter in the Kruger National Park. *J. Grassland Soc. South Africa*, 3: 148–152.

Walker, J., Crapper, P.F. & Pendridge, L.K. 1988. The crown-gap ratio (c) and crown cover: the field study. *Australian J. Ecol.,* 13: 101–108.

Westfall, R.H. & Panagos, M.D. 1984. A cover meter for canopy and basal cover Estimations. *Bothalia*, 15: 241–244.

Williams, J.B. & Rosenberg, L.J. 1993. Operational reception, processing and application of satellite data in developing countries: Theory and practice. *In* K. Hilton, ed. *Towards operational applications,* Proceedings of 19th Annual Conference of the Remote Sensing Society, Chester, UK, 16–17 September 1993.

12. Gobi Forage Livestock Early Warning System

Jay P. Angerer
Texas A&M University System, Blackland Research and Extension Center
720 E. Blackland Road Temple, TX 76502-9622, USA
Email: jangerer@brc.tamus.edu

12.1 BACKGROUND

The ability to inventory forage biomass over large landscapes can be an important component in the assessment of drought impacts, natural resource management options, environmental degradation, and changing climate. For Mongolian herders, an understanding of forage biomass availability in the surrounding landscape can assist in determining whether to move, buy or sell animals, and assess the level of risk for decision-making. However, the time and resources required to conduct accurate assessments of forage biomass over large landscapes are prohibitive, and in many areas such as Mongolia, the infrastructure and funding does not exist to conduct a comprehensive national characterization.

Another complicating factor is that decisions regarding livestock movement and stocking/de-stocking may require near real-time information, especially in the face of drought or severe winter weather events (*dzud*[12]). Forage quantity assessment is almost impossible to conduct over large land areas on a near real-time basis because of logistical and time constraints, thus the information needed for livestock related decisions is not always available when it is needed most. The inability to make decisions at critical times could lead to vegetation overuse which, in turn, can lead to environmental degradation.

During the period from 1999 to 2001, as much as 35 percent of Mongolia's livestock were lost to drought and dzud. In the Gobi region of the country, livestock mortality reached 50 percent, with many households losing entire herds (Siurua and Swift, 2002). Due to these extreme losses and their impact on pastoral livelihoods, the United States Agency for International Development (USAID), through the Global Livestock Collaborative Research Support Program (GL-CRSP) initiated the Gobi Forage Livestock Early Warning System in 2004. The Livestock Early Warning System (LEWS) technology, originally developed in East Africa (Stuth *et al.*, 2003a; Stuth *et al.*, 2005), combines near real-time weather, simulation modelling and remote-sensing data to monitor and forecast livestock forage conditions so that pastoralists and other decision-makers have information for timely decision-making in the face of drought and other disasters. For the Gobi Forage LEWS, Texas A&M University and Mercy Corps partnered to implement the forage monitoring

[12] Mongolian term for an extremely snowy winter in which livestock are unable to find fodder through the snow cover, and large numbers of animals die due to starvation and the cold. The term is also used for other meteorological conditions, especially in winter, that make livestock grazing impossible.

technology in eight *aimags* (provinces) that encompass the area where drought impacts were greatest during the 1999 to 2001 period (Figure 12.1). The goal of the Gobi Forage LEWS was to develop a forage monitoring system that would provide near real-time spatial and temporal assessment of current and forecasted forage conditions. This information would be delivered to herders to assist in their risk assessment and also be provided to local, regional and national government agencies to assist in their drought management, disaster preparedness and agricultural policy efforts.

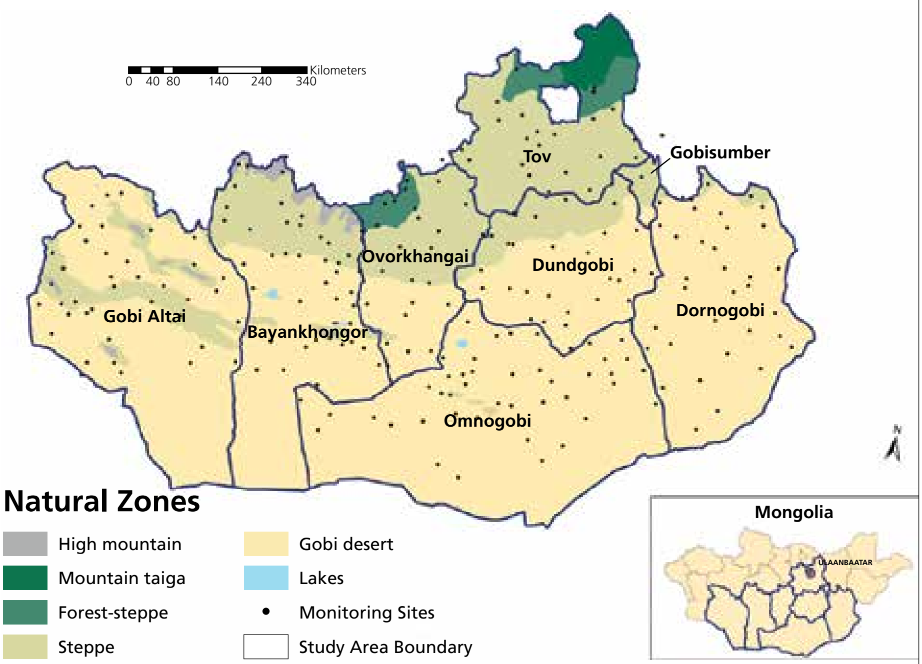
12.2 INPUTS

12.2.1 Project area

Mongolia is a landlocked country with a land area of over 1.5 million square kilometres of which over 90 percent are rangelands. Herders extensively graze their animals during the spring, summer and autumn, then return to protected camps for the winter months (Bedunah and Schmidt, 2004). Sheep and goats are the predominant forms of livestock, followed by cattle, horses, yaks and camels.

Mongolia's climate is continental with extremely cold, dry winters and warm summers. Precipitation generally occurs in the form of rainfall during the summer months (June–August) which coincides with the growing season for most plants. Precipitation is most

FIGURE 12.1
Location of aimag (province) boundaries and natural zones within the Gobi Forage LEWS project area



Note: The five natural zones generally follow the north to south gradient of elevation within the study area. Location of monitoring sites are depicted as the black dots on the map.

abundant in the northern regions of the country, averaging 200 to 350 mm per year, and least abundant in the southern regions which average 100 to 200 mm. A large portion of the country is prone to extreme winter disasters (*dzuds*) which are periods of intensely cold temperatures (< –40 °C) accompanied by snow and/or ice. *Dzuds* usually follow periods of summer drought which can lead to large losses of livestock because animals are in poor condition going in to winter and do not have enough body fat to survive the extreme winter temperatures.

This Gobi Forage LEWS was implemented in the Gobi region of Mongolia (Figure 12.1). The area includes the administrative *aimags* (provinces) of Gobi Altai, Bayankhongor, Ovorkhangai, Omnogobi, Dundgobi, Dornogobi, Gobi Sumber and Tov. Within this region, five natural zones exist that generally follow the north to south elevational gradient and include the High Mountain, Mountain Taiga (Forest), Forest Steppe, Steppe and Gobi Desert zones (Yunatov *et al.*, 1979). The High Mountain zone represents areas above the tree line and consists mainly of tundra vegetation. The Mountain Taiga zone is dominated by forest species, mainly Siberian larch (*Larix sibirica*) and Siberian pine (*Pinus sibirica*). The Forest Steppe zone represents a transition between the Mountain Taiga and Steppe zones and consists of grasslands interspersed with forested areas. Trees such as Siberian larch (*Larix sibirica*) and Siberian pine (*Pinus sibirica*) can be found on north slopes and *Stipa* and *Festuca* grasses on southern slopes. The Steppe zone consists of grasslands dominated by *Stipa*, and *Cliestogenes* grass species and *Artemisia* forbs and has the largest concentration of livestock production within the study area. The Gobi Desert zone is the most arid zone (<200 mm of precipitation) with the dominant plants consisting of *Stipa* and *Allium* species and subshrubs such as *Caragayna* and *Amygdalus* species.

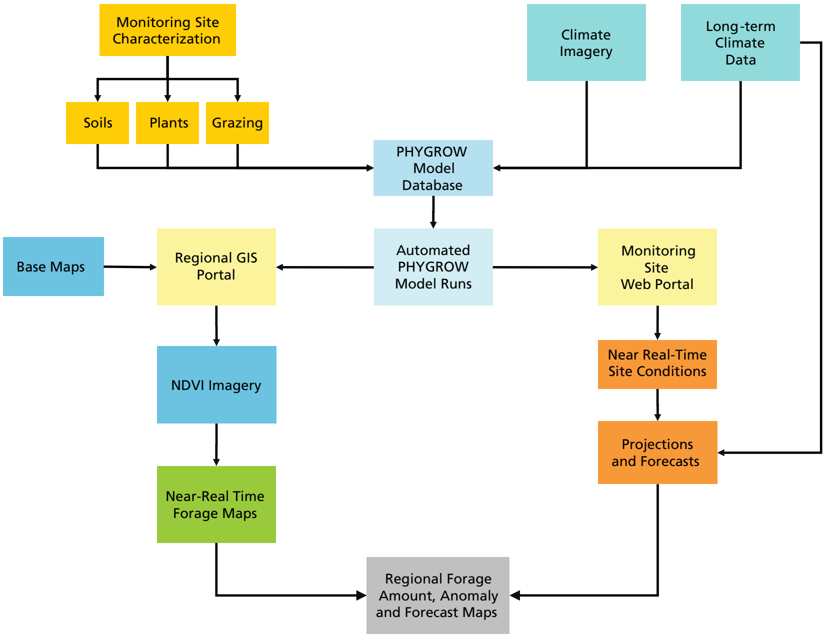
12.2.2 LEWS framework

LEWS combines field data collection from a series of monitoring sites, simulation model outputs, statistical forecasting and GIS to produce regional maps of current and forecast forage conditions (Figure 12.2). The system uses the Phytomass Growth Simulation Model (PHYGROW) (Stuth *et al.*, 2003b) as the primary tool for estimating forage conditions. Field data collected from monitoring sites established across the region are used to parameterize and calibrate the model. Model runs for the monitoring sites are driven by near real-time climate data. The simulation model runs for each monitoring site are executed every 15 days and the outputs are made available via web portal (http://glews.tamu.edu/mongolia). To produce maps of forage conditions, the total forage available to livestock is output for each monitoring site and is co-located with remote-sensing imagery data (Normalized Difference Vegetation Index [NDVI]) for the region and geostastistical interpolation is conducted to create regional maps of available forage. The LEWS system also incorporates a statistical forecasting system which provides a projection of available forage conditions for 60 days into the future.

12.2.3 Climate data sources

Climate data are acquired from the National Oceanic and Atmospheric Administration (NOAA) Climate Prediction Center (CPC). The rainfall product used as a driving variable in the forage simulation modelling was the Climate Prediction Center Morphing Product

FIGURE 12.2
Integrated framework for the Livestock Early Warning System modelling system for East Africa and Mongolia



Note: Data on plants, soils and grazers are collected from monitoring sites in the field and the data are stored in the PHYGROW model database. Climate data are acquired from national data sources and also stored in the database. The database provides data to the PHYGROW automated modelling process and the simulations are run nightly. Data are made available to the GIS portal and the Monitoring Site web portal. The GIS portal merges the simulation model outputs for the monitoring sites and with Normalized Difference Vegetation Image data. Co-kriging interpolation is used to create near real-time forage maps which are made available to regional and local stakeholders. Statistical forecasting is also conducted to provide maps and data of probable conditions.

(CMORPH) (Joyce *et al.*, 2004) (referred to hereafter as the "CMORPH product"). This product is produced by NOAA each 24-hour period and represents the accumulated rainfall that occurs between 0:00 and 24:00 Greenwich Mean Time (GMT). The CMORPH product is acquired automatically from the NOAA servers via internet and downloaded to servers at the Center for Natural Resource Information Technology (CNRIT) at Texas A&M University. The rainfall products are delivered as gridded images having a geographic range of 80.0° to 120.0° East longitude and 40.0° to 55.0° North latitude, covering the entire country of Mongolia and portions of northern China and southern Russia. Grid cell spacing of the image was 0.07276° in the longitudinal direction and 0.07277° in the latitudinal direction (approximately 8 km at the equator). During the initial comparisons of CMORPH rainfall estimates with weather station rainfall data from Mongolia, it was discovered that the product was overestimating rainfall in many locations within the study area, especially in the Steppe and Forest Steppe zones. Large overestimations occurred during the summer months (peak rainfall) and may have been related to a known problem with CMORPH and other satellite rainfall products where rainfall is detected by the rainfall algorithms, but none of the rainfall reaches the soil surface because of evaporation (Janowiak *et al.*, 2005).

To overcome this issue, a daily bias correction was calculated and applied to the product using rainfall data collected from approximately 200 weather stations within the Mongolia CMORPH domain. The station data were acquired on a near real-time basis from NOAA as part of the Global Telecommunications System (GTS) data feed. GTS is a world-wide network of climate monitoring stations that provide data to the World Meteorological Organization (WMO) as part of the World Weather Watch system. The bias-adjusted CMORPH data were used for PHYGROW simulation modelling.

Temperature data for the model were acquired from the NOAA Global Data Assimilation System (GDAS) that produces daily maximum and minimum temperature surfaces for the entire globe. Resolution of the data is 1 degree at the equator (approximately 110 km).

12.2.4 Simulation model

The PHYGROW was used for the prediction of forage biomass for monitoring sites within the study region. PHYGROW is a point model that contains four integrated submodels: climate, soil, plant growth and grazing. The model simulates a soil water balance, multi species/functional group plant growth and livestock grazing on a daily time step. PHYGROW is based on the light use efficiency model concept (Montieth, 1972; 1977) that simulates plant growth under optimal conditions (water not limiting). The model then discounts plant growth based on the amount of water stress (calculated from the water balance), temperature stress (based on species temperature tolerances for growth) and livestock grazing demand.

The model contains parameters for soil surface and layer information, plant species and community data, livestock grazing management and stocking rates, and is driven by daily climate data (Stuth *et al.*, 2003b). The soil subcomponent of the model has 13 unique parameters that include soil depth, bulk density, infiltration and water-holding capacity variables. The plant subcomponent allows simulation for individual species or functional groups. Plant community composition parameters include initial standing crop, percent basal cover for grasses, frequency of forbs, and canopy cover of shrubs and trees. For each individual plant species/functional group in the model, there are 27 plant parameters including minimum, optimal and maximum temperatures for growth, radiation use efficiency, leaf area index, leaf and wood turnover, leaf and wood decomposition, and canopy water movement. The grazing subcomponent of the model has 19 variables related to the kind/class of grazing animal including forage intake, stocking rate and grazing preference class for each plant species parameterized in the model. Lastly, the climate subcomponent has six variables which include year, day, maximum and minimum temperature, rainfall and solar radiation.

12.2.5 Monitoring site characterization

Permanent vegetation transects were established across the project area to gather information needed to parameterize the PHYGROW simulation model. Line transect and quadrat methods were used to gather plant community information and forage biomass for productivity estimates. During the initial site visit, line transect data, including basal cover of grasses and canopy cover of shrubs, were collected along with forage biomass production estimates to calibrate the model. Sites were visited periodically in the years following initial establishment to collect forage biomass data for further calibration and validation of the model.

12.2.6 Forage mapping

The geostatistical method of co-kriging was used to map forage biomass for regional maps of available forage. Co-kriging is a geostatistical interpolation method that calculates estimates for unknown points by using the weighted linear average of the available samples of the primary and secondary variables. The secondary variable (covariate) is cross-correlated with the primary variable of interest and is usually sampled more frequently and regularly (Isaaks and Srivastava, 1989), thus allowing estimation of unknown points using both variables. Forage biomass output from the PHYGROW simulation model for each of the monitoring sites was used as the primary variable in co-kriging interpolation. For the secondary variable, the Normalized Difference Vegetation Index (NDVI) data prepared by the National Aeronautics and Space Administration (NASA) Global Inventory Modelling and Mapping Studies program (Tucker *et al.*, 2005) was used. ArcGIS software was used to conduct the co-kriging interpolation and forage maps were produced every 15 days.

12.2.7 Statistical forecasting

To provide a forecast of probable future forage conditions, an auto-regressive integrated moving-average (ARIMA) (Box *et al.*, 1994) forecasting model is used. This method provides a 90-day forecast of forage conditions using time series analysis. The ARIMA approach uses modelled forage for past dates and matching historical NDVI conditions along with current forage estimates to predict future forage biomass (Alhamad *et al.*, 2007). The forage biomass values are based on 10-day moving averages.

12.3 APPROACH

The assessment of livestock forage biomass on a near real-time basis is especially important in Mongolia where drought and winter disasters (*dzud*) that deplete vegetation resources represent a major risk confronting livestock producers. Since the majority of the livestock producers are nomadic or semi-nomadic herders, knowledge of the surrounding forage conditions becomes a critical factor in risk management decision-making about livestock, especially during drought (Kogan *et al.*, 2004). Herders often respond to drought by moving livestock to another location, but the movement is not always coordinated due to the lack of information about vegetation conditions, thus leading to increased animal numbers in areas not affected by drought.

In pastoral regions, livestock is the main component of personal wealth and well-being for livestock herders. Providing early warning information on droughts or other disasters can improve marketing options for livestock prior to market crashes during drought and removing animals from drought stricken areas can reduce the likelihood of environmental impacts. Regional early warning assessments can also provide needed information to policy-makers and relief organizations to develop disaster response or mitigation strategies.

The approach for establishing the Gobi Forage LEWS in Mongolia comprised eight main activities, as follows:

1. Monitoring site selection
2. Monitoring site characterization
3. Simulation model parameterization

4. Near-real time simulation for monitoring sites
5. Integration of model output with remotely-sensed data
6. Regional mapping of forage biomass and anomalies
7. Information dissemination
8. Training on use of Gobi Forage products

Each of these activities and the methods used for implementation are discussed below.

12.4 METHODOLOGY FOR ESTABLISHING THE FORAGE INVENTORY

12.4.1 Monitoring site selection

A series of monitoring sites were established across the study area to gather information needed to parameterize the simulation model and to provide a representative sample of the forage productivity across the region. An 8 km x 8 km grid, representing the resolution of the pixels of the CMORPH rainfall data, was superimposed over the Gobi Forage LEWS project area (Figure 12.1). To ensure that sites would be accessible, the grids were stratified by selecting only those grids that were within 30 km of roads. This was done by overlaying the road network on top of the grid within the ArcGIS software and creating a spatial query to select only those grid cells that had their boundaries within 30 km of the roads. From the stratified grids, a subset of grids was randomly selected within each *aimag*, with the number of grids proportional to the land area of each *aimag* and natural zone (Figure 12.1). Once the grids were selected, these were uploaded to Personal Digital Assistants (PDAs) equipped with Global Positioning Systems and ArcPad mobile GIS software. The PDAs were given to field teams and these were used to navigate to the selected grid cells for monitoring site characterization.

12.4.2 Monitoring site characterization

The field teams used the road network to drive to within range of a selected grid, and then drove overland to the land area inside the boundaries of the grid by navigating with the ArcPad software and PDA/GPS. Once inside the grid, the dominant plant community was identified through field reconnaissance and a location for a permanent vegetation transect was established. Due to the large geographic area of the project, the permanent vegetation transects were installed in phases with the first phase occurring in the Gobi Altai, Bayankhongor and Ovorkhangai *aimags* during 2004 (Figure 12.1). In 2005, transects were established in Omnogobi, Dundgobi, Gobisumber and Dornogobi *aimags*. Transects in the Tov *aimag* were established in 2006. A total of 243 monitoring sites were installed across the region (Figure 12.1) during the monitoring site characterization phase.

To gather the necessary plant community parameters for the PHYGROW model at each monitoring site, a modified point-frame method (Ryan, 2005) was used to collect percent basal cover of grasses, frequency of forbs and shrub canopy cover along each permanent transect. Transect lengths ranged from 100 to 500m according to vegetation cover and plant spacing at the sites. Sites having sparse vegetation and low plant cover had longer transects.

Along each transect, the modified point frame (Photo 12.1) was placed on the soil surface and each point on the frame was examined to determine if it intersected the basal area

Photo 12.1
Modified point frame used to collect grass basal area, forb frequency and shrub canopy cover on Gobi Forage LEWS monitoring sites

of a grass species, plant litter, bare ground or rock. If a basal area of a grass species was encountered, this was recorded as a "hit". Within a 5 x 5 cm quadrat around each point, each presence of a unique forb species was defined as a "hit". If a shrub or tree canopy intersected an upward, perpendicular line from the point, the shrub or tree species was recorded as a "hit". A total of 250 to 500 points were sampled with the number of points sampled varying depending on vegetation cover and plant spacing. The "hits" of grass, forbs, and shrub/tree species were divided by the total possible hits and these values were entered as the plant community composition variable in the PHYGROW model.

Herbaceous biomass at each transect was measured at the time of transect establishment and in subsequent years after monitoring site establishment. A 0.25 or 0.50 m^2 quadrat was placed at equal increments along the transect (n = 10 samples per transect) and the herbaceous biomass (grass and forbs) was clipped to a 1-cm stubble height (Photo 12.2). If shrubs were located within the quadrat and they were palatable to livestock, the current year's growth was clipped from the stems of the shrub. The clipped biomass was placed in paper bags, taken back to the laboratory and dried in a forced air oven at 60 °C for 48 hours. After drying, the samples were weighed with a digital scale. The sample weights were then multiplied by the appropriate plot factor in relation to the quadrat size to convert the forage biomass to kg/ha units. The 10 samples were averaged and the mean was used for calibration and validation of the simulation model output.

For the soil components in PHYGROW, a 1:1 000 000 scale soil map was acquired from the Mongolia National Soil Laboratory. Using a GIS, the soil series information was extracted from the soil map and soil parameters were entered into the PHYGROW model. If soil data were not available for a site, a soil pit was dug and characterized during visits

Photo 12.2
Clipping of a quadrat at a Gobi Forage LEWS monitoring site

to the monitoring site. Soil samples were retrieved from the layers and sent to the National Soil Laboratory for analysis. Soil scientists were consulted to assist with soil classification. When texture parameters were the only information available for a soil, model parameters were estimated from texture percentages using a soil parameter estimation tool (Saxton *et al.*, 1986).

Stocking rate information was calculated from *sum*[13] (district) censuses of livestock that were conducted during each year of the study. The total number of each kind of livestock was divided by the land area of the *sum* and this number was used as the stocking rate parameter in PHYGROW. Seasonal dry matter intake for each kind of livestock was determined through consultation with ruminant nutrition scientists at the Mongolian Agriculture University Research Institute for Animal Husbandry (RIAH).

12.4.3 Simulation model parameterization

Soil, plant and grazer data were entered into the PHYGROW centralized database that contains a relational table structure to store parameter data for each of the monitoring sites. Soil parameter data entered included soil depth for each layer, bulk density, water holding capacity variables, slope and water runoff parameters. Plant parameter data for the plant community characterization included basal area and canopy cover information collected from field visits. Species-specific and functional group-specific plant growth parameters were also entered and these included leaf area index, relative growth rate, leaf/wood turnover variables, rooting depth, plant height, and optimal growth and suppression temperatures. Species and functional group plant growth parameter data were acquired

[13] Each aimag is divided into a number of sums (districts).

from published literature and online databases such as EcoCrop (FAO, 1994) and the Global Leaf Area Index Database (Scurlock *et al.*, 2001). When no information could be found for a species, an expert judgment was made based on the plant genus, functional group and information on growth characteristics gathered from plant experts in Mongolia.

Grazer data were entered to characterize the density of livestock grazing, the monitoring site and the general characteristics of livestock management for the area where the monitoring site was sampled. Grazer parameters include a maximum and minimum stocking rate, dry matter intake of the grazer and grazing preferences for the plants that occupy the site. Preferences were entered for each species and functional group and represent whether the grazer considers the species as preferred, desirable, undesirable or non-consumable for different plant growth stages such as rapidly growing, dormant or dead.

Climate data were downloaded on a daily basis from the NOAA servers and stored on the PHYGROW servers. Maximum and minimum temperature and bias-corrected rainfall were extracted from the NOAA data using the latitude and longitude of the monitoring site and stored in the PHYGROW database for use in the simulation model run for each site.

12.4.4 Near real-time simulation for monitoring sites

After all sites had been parameterized, PERL[14] scripts are used to extract the parameters from the database and the parameter files needed by the PHYGROW model are built for each monitoring site. Prior to near real-time simulation, each of the monitoring sites was calibrated. This involved running the model with the climate data and comparing the simulated forage biomass output to that measured during the transect establishment and subsequent biomass clipping at later dates. If the model output fell within ± 1 standard error of the mean for the forage biomass measured on the monitoring site transect, the model was considered calibrated for that data collection period. If the model output fell outside ± 1 standard error of the measured data, parameters were adjusted in an attempt to move the modelled biomass estimate to within the standard error. This process was repeated for each time period for which data were collected until the model was considered calibrated. Model parameter adjustments for calibration were limited to species maximum rooting depths, green and dead leaf turnover rates, and soil layer thickness at the surface[15] parameters. After the model was considered calibrated, the model parameters for a site were no longer adjusted and the runs were established in the queue to run on a near real-time basis.

The near real-time simulations are run on a distributed computing system. The system consists of central server connected to 20 nodes with a capacity of 80 central processing units. The central server uses the PERL scripts to extract the parameter files with the most recent weather for the 247 monitoring sites from the PHYGROW database and stores them in the run queue. The queued runs are sent to the various processing nodes and the simulations and forecasts are run. Once completed, selected outputs are stored in the PHYGROW database. Individual site outputs are made available via the project web portal at http://glews.tamu.edu/mongolia. PERL scripts extract the total forage available data from the database and prepare them for use in the forage mapping.

[14] PERL is a high-level, general-purpose, interpreted, dynamic programming language.

[15] Soil layer thickness at the surface influences the depth of soil water evaporation.

12.4.5 Integration of model output with remotely-sensed data

To prepare the data for forage mapping, a weighted average of total forage available data for all grazers is extracted from the database for all of the monitoring sites. Total forage available represents the forage available to specific grazers based on their preferences and the amount of biomass present at the monitoring site. The PHYGROW model will output total forage available for each grazer; however, an integrated total forage available dataset is created where a weighted average of the total forage available for the grazers is calculated on the basis of forage intake and stocking rate (i.e. total forage demand) of the grazers at the monitoring site. The integrated total forage available is output every 15 days with the latitude and longitude for each of the monitoring sites. The total forage available data are then co-located with NDVI data for the project region. The resulting file is used for the co-kriging interpolation to create forage maps. Long-term average total forage available and the 60-day forecast total forage available are also extracted from the database. The long-term average total forage available data are co-located with the long-term average NDVI for the same time period to create a co-kriging file in order to produce a long-term average forage map. The 60-day forecast total forage available data are co-located with a forecast NDVI image to create the 60-day forecast forage map.

12.4.6 Regional mapping of forage biomass and anomalies

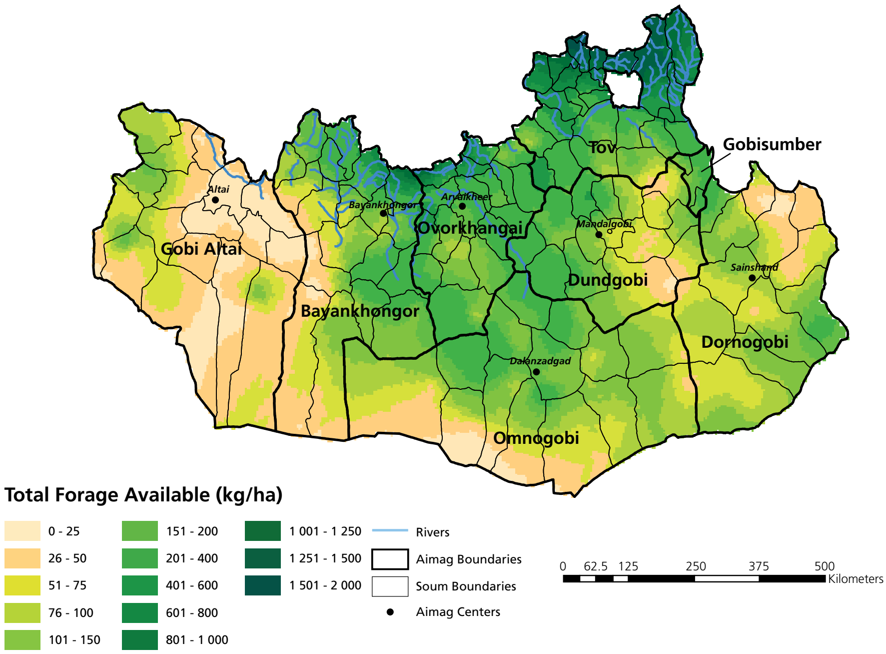
The geostatistical procedure of co-kriging (see Isaaks and Srivastava 1989 for a discussion of co-kriging) to produce landscape maps of forage production uses the co-located forage output and NDVI data. The co-kriging procedure not only uses the positive relationship between the forage biomass and the NDVI, but also accounts for spatial autocorrelation[16] to create interpolated maps of forage biomass. Co-krigings were conducted using the Geostatistical Analyst extension in the ArcGIS 9 software (ESRI, 2005).

To assess how well co-kriging predicted forage biomass, cross-validation was conducted using the ArcGIS software. Cross-validation involves dropping out data for one of the monitoring points and then running the co-kriging procedure and predicting the forage value for the point that was left out. This procedure is repeated for all the monitoring points and then the observed and predicted values can be compared via regression to assess statistically how well the co-kriging procedure performed for estimating unsampled points. The results of this exercise for forage mapping during the summer months of 2005 to 2007 indicated that the co-kriging procedure generally did a reasonable job of predicting forage biomass ($r^2 = 0.58$ to 0.69). The co-kriging procedure had a tendency to slightly underpredict forage biomass by 1 to 4 percent (Angerer, 2008).

Total forage available maps representing current forage conditions are produced bimonthly (Figure 12.3). To provide a spatial representation of forage anomalies, a forage deviation map is also produced (Figure 12.4). This is calculated by performing a standardized deviation between the current forage map and the long-term average forage map for the period of interest. The deviations are categorized into early warning indicators to delineate areas of drought intensity (Figure 12.4). A 60-day forecast map of projected forage conditions is produced to provide information for assessing drought risk (Figure 12.5).

[16] Spatial autocorrelation refers to the "rule" that items closer together in space are generally more similar than those farther apart.

FIGURE 12.3
Map of total forage available for Gobi Forage LEWS project area between 1 and 15 September 2007



12.4.7 Information dissemination

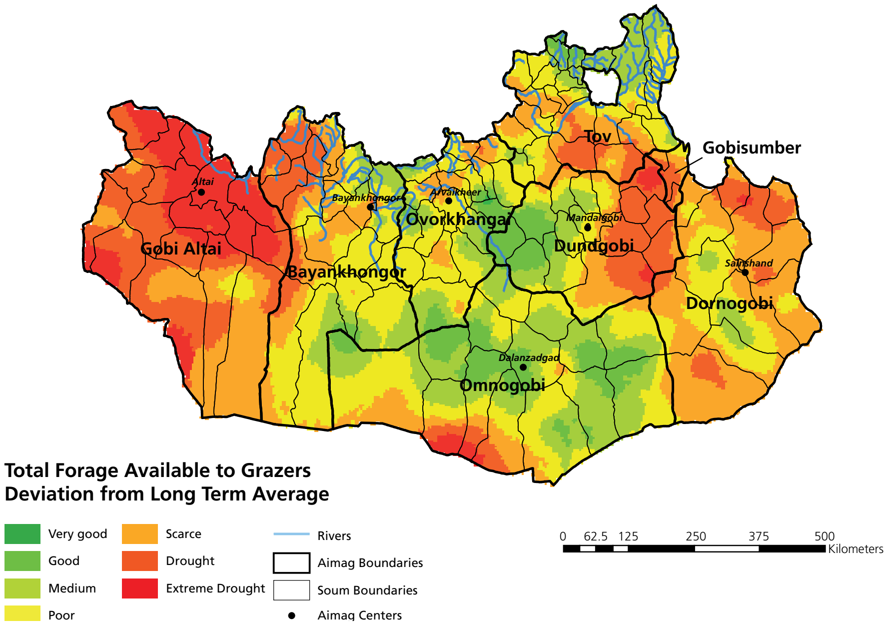
Current, forecast and long-term deviation forage maps are produced bimonthly and are distributed via the internet (http://glews.tamu.edu/mongolia) and email. The maps are also printed in colour and mailed to *sum* governments for local government use and for posting on the local government bulletin boards. Maps are also provided to regional and national government officials. A situation report, representing an interpretation of the forage maps by a rangeland specialist, is produced and mailed to regional and national government officials. This report is also used to produce radio bulletins that are reported on Mongolian National Public Radio.

12.4.8 Training on use of Gobi Forage products

Training programmes for herders, government personnel, NGOs and other interested stakeholders in the use and interpretation of the LEWS products were developed. Gobi Forage personnel travelled to *sums* across the region and conducted training sessions for herders and local government personnel to introduce them to the Gobi Forage products and to provide instruction on interpretation of Gobi Forage maps (Photo 12.3). Training was enhanced by the production of a set of DVD videos that were distributed, as well as shown, at the training sessions. These videos proved to be very effective tools for introducing potential users to the Gobi Forage programme by providing a description of both the LEWS meth-

FIGURE 12.4

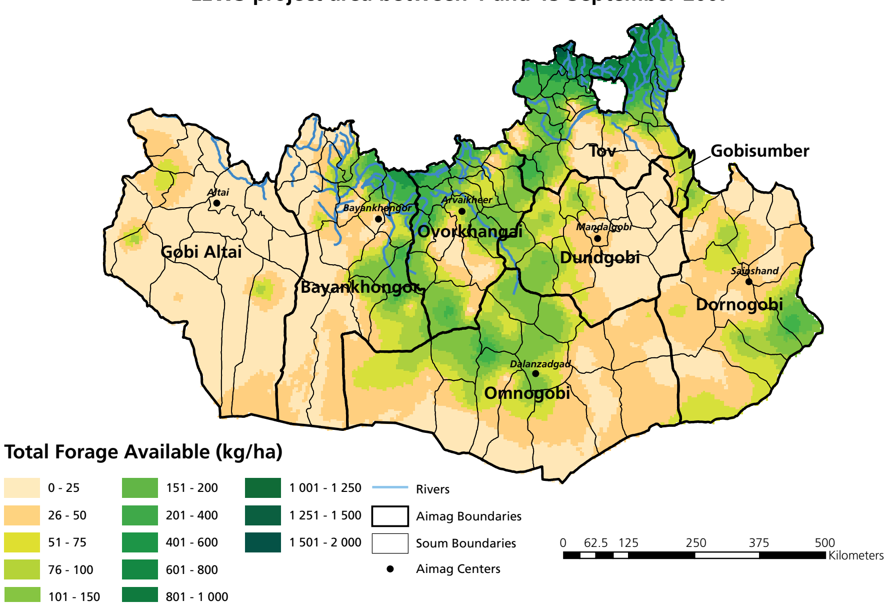
Map of total forage available deviation from long-term average for Gobi Forage LEWS project area between 1 and 15 September 2007



Note: Deviation categories represent early warning indicators on severity of drought – observe the severity of drought in east Dundgobi and northern Gobi Altai aimags.

FIGURE 12.5

Map of total forage available projected 60 days into future for Gobi Forage LEWS project area between 1 and 15 September 2007



Note: Forage amounts represent the forecast biomass available for 1-15 November 2007.

Photo 12.3
Training sessions held for herders and local government officials to introduce them to Gobi Forage maps and to assist them in using maps for risk management decision-making

odology and products. Brochures, calendars and descriptive maps were also produced for distribution after training sessions to improve retention of information by trainees.

A survey conducted during 2008 in the region indicated that the Gobi Forage programme was well received, with over 70 percent of herders having some degree of familiarity with Gobi Forage products. Almost half of the surveyed herders reported that they had used Gobi Forage information to guide livestock movements (51 percent), provide supplemental feed (49 percent) or change their grazing strategy (40 percent). An overwhelming majority (93 percent) of government officials found Gobi Forage products to be "very useful" in advising herders on grazing management and livestock movement. One provincial governor described how the system helped him manage the influx of almost 50 000 herders and their families from a neighbouring drought-stricken *aimag* and prevented conflict with local herders.

12.5 UPDATING THE FORAGE INVENTORY

Because of the early warning nature of the Gobi Forage LEWS programme, the forage inventory is updated continuously with the bimonthly processing of monitoring site data and the production of forage maps. Subsets of the monitoring sites throughout the region are visited periodically to collect forage biomass data to verify model predictions. In addition, vegetation transect data are collected periodically (every 3 to 5 years) for monitoring vegetation change and to update monitoring site parameters in the model if vegetation conditions have changed.

After USAID funding for the project ended in 2008, funding for continuation of the programme was received from the World Bank's Sustainable Livelihoods Programme in Mongolia. With the World Bank funding, the monitoring area has been expanded to include all of Mongolia and has since been renamed as the Mongolia Livestock Early Warning System. Forage mapping for the entire country will be initiated by mid-2012. By 2013, the system will be institutionalized at the Mongolia National Agency for Meteorology, Hydrology and Environment Monitoring (NAMHEM).

12.6 REFERENCES

Alhamad, M. N., Stuth, J. & Vannucci, M. 2007. Biophysical modelling and NDVI time series to project near-term forage supply: spectral analysis aided by wavelet denoising and ARIMA modelling. *Int. J. Remote Sens.,* 28: 2513–2548.

Angerer, J. P. 2008. *Examination of high resolution rainfall products and satellite greenness indices for estimating patch and landscape forage biomass*. Texas A&M University, College Station, Texas. 120 pp. (PhD Thesis).

Bedunah, D. J. & Schmidt, S. M. 2004**.** Pastoralism and protected area management in Mongolia's Gobi Gurvansaikhan National Park. *Develop. Change,* 35(1): 167–191.

Box, G., Jenkins, G. & Reinsel, G. 1994. *Time series analysis: Forecasting & control (3rd Edition),* Prentice Hall, New Jersey, USA.

ESRI. 2005. *ArcGIS 9: Using ArcGIS geostatistical analyst.* Redlands, ESRI, California, USA.

Isaaks, E. H. & Srivastava, R. M. 1989**.** *Applied geostatistics.* Oxford University Press, New York, USA.

Janowiak, J. E., V. E. Kousky, and R. J. Joyce. 2005**.** Diurnal cycle of precipitation determined from the CMORPH high spatial and temporal resolution global precipitation analyses. *J. Geophys. Res.,* 110: D23105.

Joyce, R. J., Janowiak, J. E., Arkin, P. A. & Xie, P. P. 2004. CMORPH: A method that produces global precipitation estimates from passive microwave and infrared data at high spatial and temporal resolution. *J. Hydromet.,* 5(3): 487–503.

Kogan, F., Stark, R., Gitleson, A., Jargalsaikhan, C., Dugrajav, C. & Tsooj, S. 2004. Derivation of pasture biomass in Mongolia from AVHRR-based vegetation health indices. *Int. J. Remote Sens*., 25(14): 2889–2896.

Montieth, J. L. 1972. Solar radiation and productivity in tropical ecosystems. *Appl. Ecol.,* 9: 747–766.

Montieth, J. L. 1977. Climate and efficiency of crop production in Britian. *Philosoph. Trans. Royal Soc. London, Series B,* 281: 277–294.

FAO. 1994*. Ecocrop Version 1.1*. Rome. Italy.

Ryan, Z. 2005. *Establishment and evaluation of a livestock early warning system for Laikipia*, Kenya. Texas A&M University. College Station, Texas, USA. PhD Thesis.

Saxton, K. E., Rawls, W. J., Romberger, J. S. & Papendick, R. I. 1986. Estimating generalized soil-water characteristics from texture. *Soil Sci. Soc. America J.,* 50(4): 1031–1036.

Scurlock, J. M. O., Asner, G. P. & Gower, S. T. 2001. *Global leaf area index data from field measurements, 1932–2000*. Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, USA.

Siurua, H. & Swift, J. 2002. Drought and zud but no famine (yet) in the Mongolian herding economy. *Inst. Develop. Studies Bulletin* 33: 88–97.

Stuth, J. W., Angerer, J., Kaitho, R., Jama, A. & Marambii, R. 2005. Livestock early warning system for Africa rangelands. *In* V. K. Boken, A. P. Cracknell & R. L. Heathcote, eds. *Monitoring and predicting agricultural drought: a global study*, Oxford University Press, New York, USA. 472 pp.

Stuth, J.W., Angerer, J., Kaitho, R., Zander, K., Jama, A., Heath, C., Bucher, J., Hamilton, W., Conner, R., & Inbody, D. 2003a. The livestock early warning system (LEWS): Blending technology and the human dimension to support grazing decisions. Arid lands newsletter, University of Arizona. Available at http://cals.arizona.edu/OALS/ALN/aln53/stuth.html.

Stuth, J. W., Schmitt, D., Rowan, R. C., Angerer, J. P. & Zander, K. 2003b. *Phygrow Users Guide and Technical Documentation*. Texas A&M University, College Station, Texas, USA.

Tucker, C. J., Pinzon, J. E., Brown, M. E., Slayback, D. A., Pak, E. W., Mahoney, R., Vermote, E. F. & El Saleous, N. 2005. An extended AVHRR 8-km NDVI dataset compatible with MODIS and SPOT vegetation NDVI data. *Int. J. Remote Sens.,* 26(20): 4485–4498.

Yunatov, A. A., Dashnima, B. & Gerbikh, A. A. 1979. *Vegetation Map of the Mongolian People's Republic*. Naukia. Moscow, Russia.

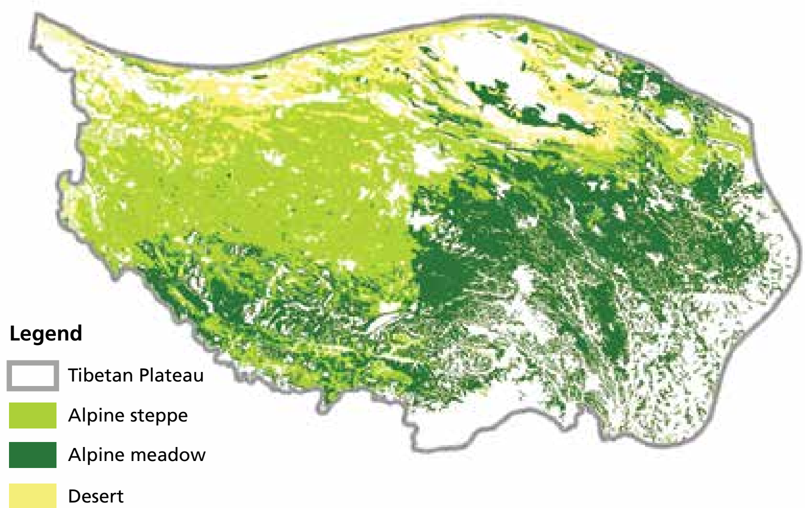
13. Livestock feed inventory on the Tibetan Plateau by remote sensing and *in situ* observation

Xiangming Xiao, Jinwei Dong, Chandrashekhar Biradar and Sage Sheldon
Department of Microbiology and Plant Biology, and Center for Spatial Analysis, University of Oklahoma, Norman, OK 73019, USA
Email: xiangming.xiao@ou.edu

13.1 THE NEED FOR A LIVESTOCK FEED INVENTORY ON THE TIBETAN PLATEAU

The Tibetan Plateau, also known as the Qinghai-Tibetan Plateau, is the largest and highest plateau in the world (Figure 13.1). It covers an area of 2.5 million km^2, with an average elevation of 4 500 m above sea level, and is often called "the roof of the world". The Plateau includes the Tibetan Autonomous Region (TAR), Qinghai Province of China, and parts of Sichuan, Gansu and Yunnan provinces. The population of the Tibetan Autonomous Region increased from 1.23 million in 1959 to 2.93 million in 2010. This increased population has brought great demand and pressure on natural resources and the environment.

FIGURE 13.1
Grassland types of Tibetan Plateau including alpine steppe and alpine meadow



Due to the extreme climatic conditions on the Tibetan Plateau, its alpine meadow, alpine steppe, desert and forest ecosystems are fragile. With a total area of 1.5 million km^2 of pasture, the major livestock on the Plateau are yak and sheep, and its livestock population has doubled over the last 40 years. The total number of livestock in Qinghai and Tibet provinces in 2004 was 8735×10^4 standard sheep (yak was converted into sheep for uniform unit).

Primary production and aboveground biomass of natural grasslands has substantial seasonal and inter-annual fluctuations because of changing weather and climate. The field data show that the grassland primary productivity in the Three River Sources Region has a cyclical fluctuation over 3–5 years (Fan *et al.*, 2010). The feedstock yields in the region have shown an increasing trend over the last few years, particularly in the alpine grassland steppe, but it is likely to be a short-term phenomenon. The overall effects of climate change on grassland ecosystem productivity are likely to be negative over a long-term period on the Plateau (Fan *et al.*, 2010).

Climate change and increasing human activities will continue to increase the uncertainty and instability of grassland ecosystems. Drought on the Tibetan Plateau and overgrazing by livestock have accelerated grassland degradation (Liu *et al.*, 2008). Many regions on the Plateau have experienced environmental pollution and ecological damage (Cheng and Shen, 2000). Land desertification on the Plateau has increased substantially, particularly in a large area of Qinghai Province, which now accounts for approximately 21 percent of the total area of desertification in China. Soil erosion has also increased, in particular along the Hengduan Mountains where deforestation and other man-made disturbances occurred extensively. Biodiversity has decreased rapidly due to environmental degradation, over-excavation and hunting.

A livestock feed inventory can provide information on feed availability over time and space, which is critically needed to support feedstock management of individual herders and livestock industry. It is of great significance for utilizing and managing grassland, as well as improving ecological balance and environment. On the Tibetan Plateau, natural grassland is the only feed resource for livestock. An effective feed inventory system with a focus on grasslands will be very helpful for the livestock industry and ecosystem protection. Remote sensing could play an important role in the feed inventory at the regional level. Field investigations on the Tibetan Plateau region are difficult because of low oxygen levels and remote locations, so ground data are very limited. Our strategy is to integrate remote sensing-based modelling and flux tower-based *in situ* observations to develop a real-time system of monitoring gross and net primary production on the Tibetan Plateau. Regional aboveground biomass and forage will also be estimated with a remote sensing-based approach. The flux towers will provide data needed to validate our results. The workflow is shown in Figure 13.2.

In this document, we focus on the methods and procedures for estimating gross and net primary production, aboveground biomass and edible forage for livestock in grasslands of the Plateau (Figure 13.2). The first part of the document introduces methods and procedures for estimating gross and net primary production of grasslands from a satellite-based approach. We will briefly discuss the satellite-based Vegetation Photosynthesis Model (VPM) as a diagnostic model for estimating gross and net primary production of terrestrial ecosystems (Xiao *et al.*, 2005a; Xiao *et al.*, 2005b; Zhang *et al.*, 2005; Zhang *et al.*, 2006). The second part of the document discusses satellite-based approaches for estimating aboveground biomass, which include using data from optical sensors such as Landsat and Moderate Resolution Imaging Spectroradiometer (MODIS) (Friedl *et al.*, 1994; Ikeda *et al.*, 1999; Hirata, 2000; Weiss *et al.*, 2001; Schino *et al.*, 2003; Benie *et al.*, 2005; Xu *et al.*, 2008; Yang *et al.*, 2009a; Yang *et al.*, 2009b)

13.2 GROSS AND PRIMARY PRODUCTION OF GRASSLANDS

13.2.1 The Vegetation Photosynthesis Model (VPM)

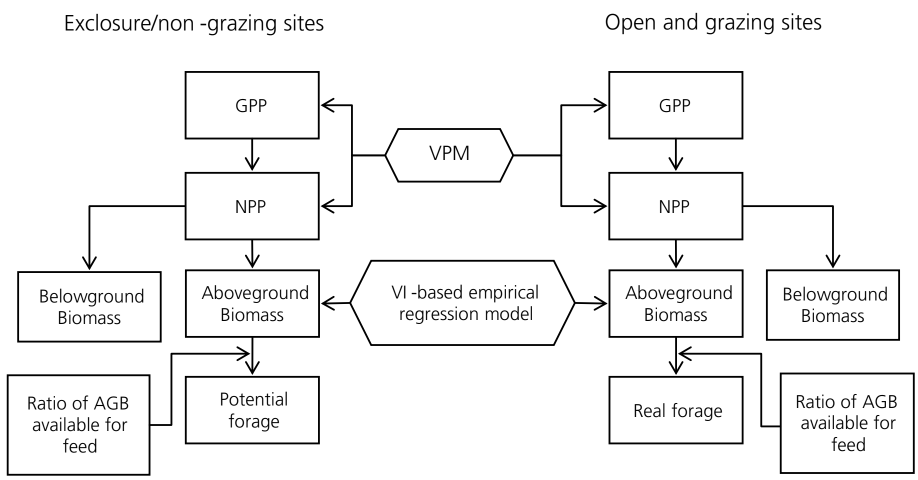
From a biochemical perspective, vegetation canopies are composed of chlorophyll (chl) and non-photosynthetic vegetation (NPV). The latter includes both canopy-level (e.g. stem, senescent leaves) and leaf-level (e.g. cell walls, vein and other pigments) materials. Therefore, $FPAR_{canopy}$ should be partitioned into the fraction of photosynthetically active radiation (PAR) absorbed by chlorophyll ($FPAR_{chl}$) and the fraction of PAR absorbed by NPV ($FPAR_{NPV}$) (Xiao *et al.*, 2004a; Xiao *et al.*, 2004b; Xiao *et al.*, 2005a):

$$Canopy\ (g/m2) = chlorophyll\ (g/m2) + NPV\ (g/m2) \quad (1)$$

$$FPAR_{canopy} = FPAR_{chl} + FPAR_{NPV} \quad (2)$$

Plant photosynthesis starts with light absorption by leaf chlorophyll. The PAR absorbed by chlorophyll (product of $FPAR_{chl} \times PAR$) is responsible for photosynthesis or gross primary production (GPP). Based on the conceptual partitioning of chlorophyll and NPV within a leaf and canopy, the VPM was developed for estimating GPP over the photosynthetically active period of vegetation (Xiao *et al.*, 2004b). The VPM is briefly described as the following:

FIGURE 13.2
Feed inventory system based on remote sensing and *in situ* observation on the Tibetan Plateau



$$GPP = \varepsilon_g \times FPAR_{chl} \times PAR \quad (3)$$

In the first version of the VPM, $FPAR_{chl}$ within the photosynthetically active period of vegetation is estimated as a linear function of Enhanced Vegetation Index (EVI), and the coefficient *a* is set to be 1.0 (Xiao *et al.*, 2004a; Xiao *et al.*, 2004b):

$$FPAR_{chl} = a \times EVI \quad (4)$$

Light use efficiency (ε_g) is affected by temperature, water and leaf phenology:

$$\varepsilon_g = \varepsilon_0 \times T_{scalar} \times W_{scalar} \times P_{scalar} \quad (5)$$

where ε_0 is the apparent quantum yield or maximum light use efficiency (μmol CO_2/μmol PPFD[17]), and T_{scalar}, W_{scalar} and P_{scalar} are the scalars for the effects of temperature, water and leaf phenology on the light use efficiency of vegetation, respectively. The full description of the VPM is given elsewhere (Xiao *et al.*, 2004c; Xiao *et al.*, 2005a).

The VPM has been evaluated over several major biome types, including tropical rainforest (Xiao *et al.*, 2005b), temperate deciduous broadleaf forest (Xiao *et al.*, 2004b; Wu *et al.*, 2009; Wu *et al.*, 2010), evergreen needleleaf forest (Xiao *et al.*, 2004a; Xiao *et al.*, 2005a), alpine tundra (Li *et al.*, 2007b), grassland (Wu *et al.*, 2008; Wang *et al.*, 2010b), winter wheat, and corn croplands (Yan *et al.*, 2009). The VPM model was also applied to estimate GPP on the Tibetan plateau (Li *et al.*, 2007b), and the results showed that the VPM-predicted GPP agreed reasonably well with the estimated GPP from three CO_2 eddy flux tower sites in alpine meadow, alpine wetlands and alpine grasslands. These results demonstrated the potential of the satellite-driven VPM model for scaling-up the GPP of alpine grassland ecosystems.

13.2.2 Satellite images and climate data for simulations of the VPM model

The VPM model uses the EVI and Land Surface Water Index (LSWI), derived from imagery from optical sensors such as MODIS on board the Terra and Aqua satellites. MOD09A1 MODIS products are downloaded from the USGS EDC data centre[18], which includes surface reflectance values of bands 1–7 at 500 m resolution and an 8-day temporal resolution.

The VPM model also uses air temperature and PAR as input data. The air temperature data is derived from the China Meteorological Data Sharing Centre. The daily air temperature was combined into an 8-day average and interpolated to produce wall-to-wall gridded data coverages. PAR was derived from the Total Ozone Mapping Spectrometer (TOMS) ultraviolet reflectance data in point format. The PAR was calculated using the method of Eck and Dye (1991) and Li *et al.* (2007A), and then the PAR point data was interpolated into grids.

[17] Photosynthetic photon flux density.

[18] Earth Resources Observation and Science (EROS) Center.

13.2.3 *In situ* observations from CO2 flux tower sites for evaluation of the VPM model

There are three CO_2 flux towers available in Maqu, Haibei and Damxung on the Tibetan Plateau, which collect data for alpine meadow, alpine meadow and alpine steppe-meadow, respectively. All the three flux towers (Table 13.1) provide observational data for parameter calibration in models and validation.

The Maqu flux measurement site is located in Maqu county, Gansu province, China (37°52.77′ N, 102°09.27′E), on the eastern, protuberant edge of the Tibetan Plateau. A number of different ecosystems are present in this area. The climate of this region is cold and humid, which is typical in alpine areas. The mean annual temperature of this site is 1.1 ℃. There are only 19 days without frost throughout the year. Mean annual precipitation is 560 mm. Vegetation in this area is typically alpine meadow, dominated by gramineous species. The main soil types are alpine meadow soils and swamp soils.

The Haibei flux observation site is located at the Haibei Alpine Meadow Ecosystem Experimental Station (37°29′ ~ 37°45′N, 10112′ ~ 101°23′E), geographically situated in the northeastern part of the Qinghai-Tibetan Plateau. The altitude of this area ranges from 3 200 m to 3 600 m. The climate of this region is highly continental, and has been termed "plateau continental". Mean annual temperature is around -1.7 °C. Annual precipitation is about 600 mm with most precipitation occurring in summer. Vegetation in this area is the typical alpine vegetation of the Northern Qinghai-Tibetan Plateau. The main soil types are alpine meadow soils, alpine scrubby meadow soils and swamp soils.

The Damxung flux measurement site is located north of the Lhasa municipality and near to the southern edge of the Nyainqntaglha Mountains (91°05′E, 30°25′N) with an elevation of 4 333 m. The experimental site is categorized as plateau monsoon climate with strong radiation, low air temperature, large diurnal variation and small annual differences. Mean annual temperature is 1.3 °C and mean annual precipitation is 476.8 mm. Mean annual evaporation is 1 725.7 mm and average wetness coefficient is 0.28. The vegetation at the Damxung site is alpine steppe-meadow, with *Kobresia* meadows typical of the northern Tibetan Plateau. There are two typical meadows at the site. One is marsh meadow dominated by *Kobresia littledalei*, associated with *Blysmus sinocompressu, K. microglochin* and *K. littledalei*. The other is dominated by *K. parva*, with subdominants species such as *K. Humilis* and *Stipa purpurea* and occasional tussocks of *Kobresia* and forbs.

TABLE 13.1
The three CO_2 flux tower sites on the Tibetan Plateau

Station name	Location	Ecosystem types	Manager
Maqu	102.15°E 37.88°N	Alpine meadow	Shihua Lv
Haibei	101.33°E 37.66°N	Alpine meadow	Xinquan Zhao
Damxung	91.08°E 30.41°N	Alpine steppe-meadow	Peili Shi

13.2.4 Net primary production of grassland

When monitoring the C^{13} isotope and effects of CO_2 doubling on the photosynthesis of sunflowers, Cheng *et al.* (2000) found that the ratio between net primary productivity and gross primary productivity was constant. Here we assume that plant respiration is proportional to gross primary productivity; and therefore, net primary production is calculated as: NPP = GPP×α.

13.3 ABOVEGROUND BIOMASS OF GRASSLANDS

Grasslands in the Tibetan Plateau are dominated by alpine steppe and alpine meadow, which cover more than 60 percent of its area. The total aboveground biomass of alpine grasslands was estimated to be approximately 77.6 Tg (1 Tg = 10^{12} g), accounting for about one-quarter of total aboveground biomass storage in China's grasslands (298.0–323.1 Tg) (Ni, 2004; Yang *et al.*, 2009b).

13.3.1 Estimation of aboveground biomass from remote sensing

There have been a limited number of studies on grasslands on the Plateau. Most of them have focused on net primary productivity and few of them have specifically examined aboveground biomass or estimated forage (Piao and Fang, 2002; Zhou *et al.*, 2004; Chen, 2009). In recent years, with government investment, some regions such as the Three River Sources region have attracted more attention, resulting in more data collection of aboveground biomass and feedstock in the grasslands.

Aboveground biomass is often estimated using simple regression models that are based the correlations between aboveground biomass and vegetation index. The correlations between *in situ* aboveground biomass measurements, various spectral bands and vegetation indexes have been established by using statistical methods (Friedl *et al.*, 1994; Ikeda *et al.*, 1999; Hirata, 2000; Weiss *et al.*, 2001; Schino *et al.*, 2003; Benie *et al.*, 2005; Xu *et al.*, 2008). Simple regression models of the following general form were widely used:

$$\textit{Aboveground biomass} = f(VI) \qquad (6)$$

A recent study has evaluated six statistical models to estimate aboveground biomass, using *in situ* biomass data in Southern Gansu Province, Northeastern Tibetan Plateau (LIANG *et al.*, 2009): a linear model, an exponential model, a growth model, a logarithm model, a power model and a polynomial model. Their results showed that the power model has better estimation accuracy, and EVI has better performance than NDVI. The best-fit simple regression model is: $AGB\ (kg/ha) = 13583 \times EVI^{1.665}$, where AGB is aboveground biomass, EVI is the value of MODIS-EVI.

Another study has evaluated eight vegetation indices for estimating aboveground biomass (Shen *et al.*, 2008), and the results showed that all the eight vegetation indices have the ability to provide good estimation of aboveground biomass. The vegetation index based on universal pattern decomposition (VIUPD) is the best predictor of aboveground biomass among simple regression models. Moreover, both VIUPD and the soil-adjusted vegetation index (VI) could provide accurate estimates of aboveground biomass with dummy variables integrated in regression models.

A recent study has reported *in situ* aboveground biomass data from 675 plots in 135 sites (i.e. five plots from each site) measured on the Tibetan Plateau during the summers (July and August) of 2001–2004); and a simple regression model between aboveground biomass and growing season EVI during the period of 2001–2004 (Yang *et al.*, 2009a; Yang *et al.*, 2009b) was developed (see equation 7). That study investigated the allocation between above- and belowground biomass in alpine grasslands and its relationship with environmental factors using field data, proving that the median values of the ratio of below-ground biomass and aboveground biomass is 5.8 on the Tibetan plateau. This ratio was significantly higher in temperate grasslands than in alpine grasslands (Wang *et al.*, 2010a).

$$AGB = 334.39 \times EVI + 10.051 \quad (7)$$

Here we use the simple regression model from Yang *et al.* (2009a,b) for estimating aboveground biomass. The EVI is calculated as the following:

$$EVI = G \times (\rho_{nir} - \rho_{red}) / (\rho_{nir} + (C1 \times \rho_{red} - C2 \times \rho_{blue}) + L) \quad (8)$$

where G = 2.5, C1 = 6, C2 = 7.5 and L = 1; ρ_{nir}, ρ_{red} and ρ_{blue} is reflectance of blue, red and near infrared bands.

13.3.2 *In situ* aboveground biomass data for calibration and validation

A series of plots nearby the three flux towers (see section 13.2.3) needs to be sampled every year in order to provide validation data. The clipping and weighing method is a very tedious, but also the most accurate method for estimation of aboveground biomass (dry matter). First, suitable plot locations are selected; usually around five plots should be clipped in one sample but more plots are needed if the pastures are variable spatially. Second, grasses above the soil surface in a given area (usually one square metre or one square foot) are clipped and collected in paper bags. Third, the samples are dried in an oven and weighed for dry matter biomass.

13.4 FORAGE BIOMASS OF GRASSLANDS

Forage availability concerns farmers most. Forage yield is part of the aboveground biomass for livestock feed. Usually, the forage yield is based on the hypothesis that grazing is in the reasonable range of the ecosystem's self-regulation. That is, pasture is used fully without grassland degradation. The ratio of forage to biomass is a key parameter for forage estimation. However, few previous studies have referred to this parameter. Therefore, a field survey must be conducted to calculate the fraction of feed in aboveground biomass.

$$Forage = AGB \times Ratio \quad (9)$$

According to the above equation, the ratio is the key for estimating forage amount. The forage yield is affected by many factors, such as grassland types, utility period, utility type, grassland degradation situation and disasters. These factors are classified as shown in Table 13.2 (Liu, 2005).

TABLE 13.2
Ranking factors and their values for forage estimation on the Tibetan Plateau

Grassland types	Alpine steppe	Alpine meadow		
	0.48*	0.58*		
Utility period	Growing season	Wither period	Avoid grazing period	
	1.0	1.2	0	
Utility type	Grazing	Cradle		
	1.0	1.4		
Grassland degradation	No	Slight	Middle	Severe
	1.00	0.85	0.7	0.55
Disasters	No	Slight	Middle	Severe
	1.00	0.85	0.70	0.55

* These values are revised from the previous study (Liu, 2005)

Therefore, the ratio of forage to aboveground biomass can be calculated using the following equation:

$$Forage = AGB \times f(x1) \times f(x2) \times f(x3) \times f(x4) \times f(x5) \quad (10)$$

where *AGB, x1, x2, x3, x4, and x5* are aboveground biomass, grassland type, utiliization (grazing) period, utility type, grassland degradation status and disasters, respectively.

13.5 SUMMARY

In this report, we describe a basic and simple framework for a feed inventory system on the Tibetan Plateau that integrates remote sensing and *in situ* observations. The main workflow comprises:

1. calculation of GPP and NPP on a regional scale, using a satellite-based VPM model, climate data and MODIS data at 50 m spatial resolution
2. estimation of aboveground biomass on a regional scale, using existing algorithms or from statistical analysis of field survey data; in addition, we can calculate below-ground biomass according to net primary production and aboveground biomass data
3. calculation of available forage for feedstock from aboveground biomass according to previous studies or related results from fieldwork on the Plateau.

It is very feasible to use such a remote-sensing methodology to update a livestock feed inventory on a regular basis.

13.6 ACKNOWLEDGEMENTS

The literature review and writing of this document were supported by research grants from the US National Science Foundation (NSF) EPSCoR programme (NSF-0919466) and the US National Aeronautics and Space Administration (NASA) Land Cover and Land Use Change Program (NNG05GH80G).

13.7 REFERENCES

Benie, G.B., Kabore, S.S., Goita, K. & Courel, M.F. 2005. Remote sensing-based spatio-temporal modelling to predict biomass in Sahelian grazing ecosystem. *Ecol. Model.,* 184: 341–354.

Chen, Z. 2009. *Analysis of the grassland productivity and stocking stress in Tibet Plateau. Institute of Geographic Sciences and Natural Resource Research*. Chinese Academy of Sciences, Beijing, China.

Cheng, S. & Shen, L. 2000. Approach to dynamic relationship between population, resources, environment and development of the Qinghai-Tibet Plateau. *J. Nat. Res.,* 15: 297–304.

Cheng, W., Sims, D.A., Luo, Y., Coleman, J.S. & Johnson, D.W. 2000. Photosynthesis, respiration, and net primary production of sunflower stands in ambient and elevated atmospheric CO_2 concentrations: an invariant NPP:GPP ratio? *Global Change Biol.,* 6: 931–941.

Eck, T.F. & Dye, D.G. 1991. Satellite estimation of incident photosynthetically active radiation using ultraviolet reflectance. *Remote Sens. Environ.,* 38*:* 135–146.

Fan, J., Shao, Q., Liu, J., Wang, J. & Chen, Z. 2010. Dynamic changes of grassland yield in Three River Headwater Region from 1988 to 2005. *Acta Agrestia Sinica*, 18: 5–10.

Friedl, M.A., Michaelsen, J., Davis, F.W., Walker, H., & Schimel, D.S. 1994. Estimating grassland biomass and leaf-area index using ground and satellite data. *Int. J. Remote Sens.,* 15: 1401–1420.

Hirata, M. 2000. Effects of nitrogen fertiliser rate and cutting height on leaf appearance and extension in bahia grass (Paspalum notatum) swards. *Trop. Grassl.,* 34: 7–13.

Ikeda, H., Okamoto, K. & Fukuhara, M. 1999. Estimation of aboveground grassland phytomass with a growth model using Landsat TM and climate data*. Int. J. Remote Sens.*, 20: 2283–2294.

Li, S.H., Yan, H.M., Niu, Z., Xu, W.B. & Yuan, J.O. 2007a. Satellite estimation of photosynthetically active radiation in Jiangxi province - art. no. 67902D. *In* Y. Wang, J. Li, B. Lei & J. Yang, eds. Remote sensing and GIS data processing and applications; and Innovative multispectral technology and applications, Pts 1 and 2, pp. D7902–D7902.

Li, Z.Q., Yu, G.R., Xiao, X.M., Li, Y.N., Zhao, X.Q., Ren, C.Y., Zhang, L.M., & Fu, Y.L. 2007b. Modelling gross primary production of alpine ecosystems in the Tibetan Plateau using MODIS images and climate data. *Remote Sens. Environ.*, 107: 510–519.

Liang T., Cui, X., Feng, Q., Wang, Y. & Xia, W. 2009. Remotely sensed dynamics monitoring of grassland aboveground biomass and carrying capacity during 2001–2008 in Gannan pastoral area. *Acta Pratacul. Sinica*, 18: 12–22.

Liu, J.Y., Xu, X.L. & Shao, Q.Q. 2008. Grassland degradation in the "Three-River Headwaters" region, Qinghai Province. *J. Geograph. Sci.*, 18: 259–273.

Liu, Y. 2005. *Rangeland productivity and forage-ruminant equilibrium in Inner Mongolia*. Chinese Academy of Sciences, Beijing, China.

Ni, J. 2004. Forage yield-based carbon storage in grasslands of China. *Clim. Change*, 67: 237–246.

Piao, S. & Fang, J. 2002. Terrestrial net primary production and its spatio-temporal patterns in Qinghai-Xizang Plateau, China during 1982–1999. *J. Nat. Resour.*, 17: 373–380.

Schino, G., Borfecchia, F., De Cecco, L., Dibari, C., Iannetta, M., Martini, S. & Pedrotti, F. 2003. Satellite estimate of grass biomass in a mountainous range in central Italy. *Agroforest. Syst.,* 59: 157–162.

Shen, M., Tang, Y., Klein, J., Zhang, P., Gu, S., Shimono, A. & Chen, J. 2008. Estimation of aboveground biomass using *in situ* hyperspectral measurements in five major grassland ecosystems on the Tibetan Plateau. *J. Plant Ecol.,* 1: 247–257.

Wang, L.A., Niu, K.C., Yang, Y.H. & Zhou, P. 2010a. Patterns of above- and belowground biomass allocation in China's grasslands: Evidence from individual-level observations. *Sci. China Life Sci*., 53: 851–857.

Wang, Z., Xiao, X.M. & Yan, X.D. 2010b. Modelling gross primary production of maize cropland and degraded grassland in northeastern China. *Agric. Forest Meteorol.*, 150: 1160–1167.

Weiss, E., Marsh, S.E. & Pfirman, E.S. 2001. Application of NOAA-AVHRR NDVI time-series data to assess changes in Saudi Arabia's rangelands. *Int. J. Remote Sens.*, 22: 1005–1027.

Wu, C.Y., Munger, J.W., Niu, Z. & Kuang, D. 2010. Comparison of multiple models for estimating gross primary production using MODIS and eddy covariance data in Harvard Forest. *Remote Sens. Environ.*, 114: 2925–2939.

Wu, J.B., Xiao, X.M., Guan, D.X., Shi, T.T., Jin, C.J. & Han, S.J. 2009. Estimation of the gross primary production of an old-growth temperate mixed forest using eddy covariance and remote sensing. *Int. J. Remote Sens.,* 30: 463–479.

Wu, W.X., Wang, S.Q., Xiao, X.M., Yu, G.R., Fu, Y.L. & Hao, Y.B. 2008. Modelling gross primary production of a temperate grassland ecosystem in Inner Mongolia, China, using MODIS imagery and climate data. *Sci. China Series D-Earth Sci.*, 51: 1501–1512.

Xiao, X., Hollinger, D., Aber, J.D., Goltz, M., Davidson, E.A. & Zhang, Q.Y. 2004a. Satellite-based modelling of gross primary production in an evergreen needleleaf forest. *Remote Sens. Environ.*, 89: 519–534.

Xiao, X., Zhang, Q., Braswell, B., Urbanski, S., Boles, S., Wofsy, S.C., Moore, B.I. & Ojima, D. 2004b. Modelling gross primary production of a deciduous broadleaf forest using satellite images and climate data. *Remote Sens. Environ.*, 91: 256–270.

Xiao, X.M., Hollinger, D., Aber, J., Goltz, M., Davidson, E.A., Zhang, Q.Y. & Moore, B. 2004c. Satellite-based modelling of gross primary production in an evergreen needleleaf forest. *Remote Sens. Environ.*, 89: 519–534.

Xiao, X.M., Zhang, Q.Y., Hollinger, D., Aber, J. & Moore, B. 2005a. Modelling gross primary production of an evergreen needleleaf forest using modis and climate data. *Ecol. Appl.*, 15: 954–969.

Xiao, X.M., Zhang, Q.Y., Saleska, S., Hutyra, L., De Camargo, P., Wofsy, S., Frolking, S., Boles, S., Keller, M. &, Moore, B. 2005b. Satellite-based modelling of gross primary production in a seasonally moist tropical evergreen forest. *Remote Sens. Environ.*, 94: 105–122.

Xu, B., Yang, X.C., Tao, W.G., Qin, Z.H., Liu, H.Q., Miao, J.M. & Bi, Y.Y. 2008. MODIS-based remote-sensing monitoring of grass production in China. *Int. J. Remote Sens.,* 29: 5313–5327.

Yan, H.M., Fu, Y.L., Xiao, X.M., Huang, H.Q., He, H.L. & Ediger, L. 2009. Modelling gross primary productivity for winter wheat-maize double cropping System using MODIS time series and CO_2 eddy flux tower data. *Agric. Ecosys. Environ.*, 129: 391–400.

Yang, Y.H., Fang, J.Y., Ji, C.J. & Han, W.X. 2009a. Above- and belowground biomass allocation in Tibetan grasslands. *J. Veg. Sci.*, 20: 177–184.

Yang, Y.H., Fang, J.Y., Pan, Y.D. & Ji, C.J. 2009b. Aboveground biomass in Tibetan grasslands. *J. Arid Environ*., 73: 91-95.

Zhang, Q.Y., Xiao, X.M., Braswell, B., Linder, E., Baret, F. & Moore, B. 2005. Estimating light absorption by chlorophyll, leaf and canopy in a deciduous broadleaf forest using MODIS data and a radiative transfer model. *Remote Sens. Environ.*, 99: 357–371.

Zhang, Q.Y., Xiao, X.M., Braswell, B., Linder, E., Ollinger, S., Smith, M.L., Jenkins, J.P., Baret, F., Richardson, A.D., Moore, B. & Minocha, R. 2006. Characterization of seasonal variation of forest canopy in a temperate deciduous broadleaf forest, using daily MODIS data. *Remote Sens. Environ.* 105, 189–203.

Zhou, C., Ouyang, H., Wang, Q., Dubian, Z. & Sun, Q. 2004. Estimation of net primary productivity in Tibetan Plateau. *Acta Geographica Sinica*, 59: 74–79.

14. The development of feed balances for livestock

Dr B R Cottrill
ADAS UK Ltd, ADAS, Wolverhampton, UK
Email: Bruce.Cottrill@adas.co.uk

14.1 INTRODUCTION

It is predicted that the world's population will increase by 2.3 billion over the next 20 years, and that this will be accompanied by an increase in the demand for animal products, namely milk, meat and eggs. A structured approach to planning for this increase in demand will be necessary if demand is to be met cost-effectively, with minimal social disruption and with minimal environmental impact. Part of this process requires an assessment of the available feedstocks and the requirements of the current livestock population, and this can be achieved by developing a livestock feed balance. Having done this, it is then possible to identify limitations to current levels of production and estimate the feed requirements for increasing production. A livestock feed balance can be undertaken at a local, regional or national level depending on policy requirements and the degree of accuracy required.

At its simplest level, a feed balance is a comparison between the requirements of livestock at any given time (demand) and the amount of utilizable feed (supply), and therefore provides a "snapshot" of the current situation. However, a feed balance can also identify potential shortages in feed to meet increasing demand for food, and help identify types of feed materials that might be required where shortfalls are identified. Alternatively, where a feed balance identifies a surplus of feed, it can be used to estimate the additional livestock production that the surplus might support.

This approach may also be undertaken to develop balances for specific nutrients. For example, phosphorus (P) is an essential nutrient that is often deficient in livestock diets, leading to reduced productivity and fertility. A phosphorus balance for a particular area or country can help identify where or when deficiencies might occur, and identify where and how much additional P may be needed to meet livestock needs and productivity targets.

Feed balances are usually calculated on an annual basis and, given that many feed crops, such as cereal grains, have an annual production cycle with one harvest, this may be appropriate. However, there is no reason why a feed balance may not be performed over a shorter period, and indeed there may be advantages in doing so in certain circumstances. For example, if there are periods of the year when the amount of natural grassland available for grazing animals is low, it may be appropriate to prepare a feed balance for those periods in order to establish the maximum potential livestock carrying capacity of a particular region when feeds are in limited supply. However, because the production cycles of many livestock systems do not equate to one calendar year, it is necessary to make adjustments to the feed balance to take account of the length of a particular cycle. For example, the cycle for growing and fattening pigs from weaning to slaughter may be only about 20–24 weeks in intensive production systems, but this may be followed by a period when the fattening house is empty to allow for cleaning and general maintenance before the next feeding period begins. If a feed balance is being prepared on an annual basis, it will be necessary to include both the length of the production cycle and the non-productive periods in calculating annual feed requirements and livestock production.

14.2 METHODS

In order to produce a feed balance, two sets of data and a number of processes need to be completed, and these are described below.

14.2.1 Estimating feed supply

Estimates of feed supply should be based on local, regional or national inventories. There has been considerable progress in developing techniques to estimate feeds available, and in particular forages. The merits or limitations of these are not discussed here, but depending on the specifications of the inventory and the way in which the available forages are quantified, it may be necessary to make adjustments for the following:

- Seasonality of supply
- Feed losses

Seasonality of supply: For many livestock, the availability of feeds may be reasonably consistent throughout the year. This will apply particularly to feeds such as cereal grains and conserved forages, where feeds can be stored without deteriorating in quality. However, in many regions a significant proportion of livestock, particularly ruminants, are kept under extensive farming systems, where the main or only feed may be native pasture. Seasonal changes in climate and growth stages of plants culminate in an annual cycle of forage production that peaks during the wet period and is severely limited during the dry period. As a result there may be periods of the year when grazing livestock are often unable to satisfy their nutritional requirements, resulting in lower growth rates and reproduction. It is important that where *annual* feed inventories are used, they are adjusted to take account of the peaks and troughs in supply relative to livestock numbers and their feed intake. Unless surplus feeds are conserved, e.g. forages conserved as silage or hay, then failure to do so may result in an over-prediction of available feed.

Feed losses: Despite the best husbandry and feed management practices, losses do occur; these are usually associated with harvesting and storage and in some circumstances these may be considerable. Some losses are inevitable, for example those associated with conserving forages (as silage or hay), where 30 percent or more of the dry matter may be lost as a result of field, storage and feeding out losses. Poor storage conditions for cereal grains, nuts and other crops can result in losses due to pest infestations and fungal contamination. Not only do they result in direct dry matter loss, but many are associated with the transfer of disease or production of toxins. Again, failure to adjust a feed inventory for these losses may lead to an overestimate of feed available.

In addition to forages, livestock are fed a wide variety of feeds. These may include cereal grains and co-products of cereal processing, oilseeds and oilseed meals derived from them, co-products of brewing and distilling, legume seeds, feeds derived from the manufacture of human food and animal products such as fish meal and processed animal proteins; collectively these are often termed "concentrates". In addition, tubers or root crops such as cassava, and co-products derived from processing such as sugar beet pulp, are frequently important feeds. Information on the quantities of these used in animal feeds may be obtained from a number of sources including import statistics, production records from compound feed manufacturers and feed merchants.

As with forages, some losses are inevitable as a result of transport, manufacture and storage, and it is important to include an estimate of these in any feed balance calculation.

14.2.2 Quantification of herd /flock numbers and production traits

In order to estimate the demand for feed, an estimate of the number of livestock in a region or country is needed. Where regional or national statistics are available, these should be used. However, in some situations reliable data may not be available, in which case best estimates should be obtained based on local knowledge of livestock production systems.

Many feed and nutrient balances are based on census data, which provide an indication of livestock numbers at a given time. However, livestock numbers within a region might fluctuate considerably during the course of the year and, as a result, the use of data derived at one particular point in time may be misleading when applied to a full year. Where this is the case, adjustments in estimates of livestock numbers must be made, again based on local knowledge.

In addition to data on livestock numbers, some estimate of productivity is required so that the amount of feed required to provide energy demands for maintenance, pregnancy and production can be calculated. For growing and fattening cattle, sheep, goats, pigs and meat poultry (e.g. broilers, ducks) this will require estimates of daily liveweight gain. In addition, data on the output of livestock products (eggs, milk and fibre, or wool) are necessary, while for reproductive (breeding) animals data on numbers of offspring are also required. In summary, production data are required to show:

- Productive life of mature animals;
- Numbers of animals at the beginning and end of the feed balance period (usually the beginning and end of the year;
- Herd or flock production measured as:
  - calving/lambing/kidding/farrowing frequency
  - lactation length
  - milk production
  - liveweight gain
  - output of animal products (milk, meat, eggs, wool);
- Adjustments necessary to account for climatic extremes or physical activity.

For most feed balances, it is sufficient to provide estimates of liveweight gain and product production in terms of their weight. Where data are available to show that milk composition varies significantly from the breed average, then information on the composition of milk, particularly the fat and protein contents, should be used, because energy requirements vary for milk of different composition. If detailed nutrient balances are being undertaken, for example to establish a nitrogen balance, then data on the composition of animal products and liveweight gain will be necessary. In most cases, standard values for the composition of gain and livestock products will suffice.

14.4.3 Estimating feed requirements

Feed materials vary significantly in their concentration of nutrients and the contribution they make to meet the requirements of livestock. Energy is usually the first limiting component in livestock diets, and for this reason feed balances are normally calculated in terms of the energy required by livestock and the energy supplied by feeds. Therefore the next step is to estimate the energy needed by the livestock identified in in paragraph 14.4.2.

For each class of livestock, it is necessary to calculate the energy requirements for:

- maintenance;
- pregnancy;
- production (e.g. milk yield, liveweight gain, number of eggs produced); and
- in some situations, it may also be necessary to make adjustments for exercise and for extremes of climate (heat or cold), and for exercise where this is significant.

There is no one internationally accepted unit of energy, and different energy systems have been developed for different livestock groups. For ruminants, metabolizable energy (ME) is widely used as the measure of feed energy, while net energy (NE) values (expressed as either MJ or Mcal) are used in Denmark, France, Germany, Ireland, Netherlands, North and South America, and Switzerland. In principle, there is no difference between ME and NE systems; both accept that the overall energy requirement is the sum of their energy needed for maintenance, production (milk and liveweight gain) and foetal growth. However, they differ in how energetic efficiencies are embodied within the calculation. In the ME system, energetic efficiencies are used for ration formulation and the prediction of animal performance, while in the NE system energetic efficiencies are included as part of the energy evaluation of feeds.

For pigs and poultry, digestible energy (DE), ME and NE systems have all been proposed and are used in different countries. There have been long lasting debates as to the merits of each system, but in practice differences between systems in estimating total energy requirements for livestock are relatively small.

It is not the purpose of this chapter to review these various systems or to pass judgement on their relative merits. What is important is that the system chosen is one which includes both estimates of requirements for the livestock production in the region/country concerned, and also provides tables of feed composition that are appropriate for the feeds that are available in the region or country in question. It is also important that the system chosen is one that the user is most familiar with and feels competent in working with.

Systems providing both the nutrient requirements of livestock and the composition of feeds have been published by a number of national authorities, some of which are given at the end of this chapter. In addition, a number of breed companies provide nutrient requirements for livestock for particular strains or breeds.

Using the data on livestock numbers, together with information on reproduction rates and productivity, e.g. eggs produced, numbers of pigs sold or the amount of milk produced, the energy requirements can be calculated. This can be done on a daily basis and scaled up to provide an annual estimate. Alternatively, where production data are available for a region or country, it is possible to calculate energy requirements on an annual basis. It can be done for an individual flock or herd, or on a regional or national basis depending on the scale of the feed balance, the need for precision and the data available.

Reference has been made to the publications that provide energy requirements of livestock and it is strongly recommended that these be used. However, where possible, in producing detailed feed balances, the following can be taken as indicative values for planning purposes:

Pigs

Energy required for growth at different live weights[1]:	25 kg	22 MJ ME/day
	60 kg	34 MJ ME/day
	90 kg	40 MJ ME/day
Energy required for pregnancy:		3,280 MJ ME per sow (total)
Energy required for lactation:		2,565 total[2] per litter (total)

Poultry

Laying hens: 52 weeks of lay, 340 eggs:	430 MJ ME/bird
0–17 weeks (pre-laying)	72 MJ ME/bird
Meat chickens (broilers) to 6 weeks (LW ♀2.3 kg, ♂2.7kg):	54 MJ ME/bird

Ruminants

		Sheep	Goats	Cattle
	Liveweight LW (kg)		*MJ ME/kg LW/year*	
Energy required for maintenance	30	66	77	
	40	65	71	
	50	58	68	
	60	55	65	
	70		63	
	100			63
	200			51
	300			45
	400			41
	500			39

cont.

Notes:
1 Derived from NRC (1998), Nutrient Requirements of Swine.
2 Assumes a weaning age of 40 days.

Ruminants (cont.d)

		Sheep	Goats	Cattle
			MJ ME/kg LW gain/day	
Energy required for gain	< 3 months			
	> 3 months			
	< 6 months	26 – 34	26 – 36	
	> 6 months	41 – 49	37 – 49	
	< 1 year			19 – 26
	> 1 year			32 – 42
Energy required for pregnancy		1 480 MJ ME per ewe (total)[3]	2,150 MJ ME per dam (total)[4]	14 420 MJ ME per cow (total)[5]
Energy required for lactation		2 160 MJ ME total6	5.1 MJ ME/litre	5.3 MJ ME/litre[7]

3 Assumes a 60 kg ewe carrying twins.
4 Assumes dam carrying twins (total birth weight 7.9 kg).
5 ME requirements for maintenance and pregnancy of a 600 kg housed, pregnant, non-lactating cow gaining 0.5 kg /day liveweight in addition to the foetus for a 40 kg calf.
6 Assume a lactation of 3 months; milk requires 4.7 MJ/litre.
7 For standard milk containing 4% fat and 3% protein.

14.2.4 Estimating energy supplied from available feeds

The previous steps make it possible to estimate the energy requirements of the herd or flock on a farm or on a regional or national basis. However, because most feed inventories describe the amount of feed available in terms of dry matter (DM[19]), it is necessary to convert this to the same energetic terms, i.e. MJ ME or NE in the case of ruminants, or ME or DE for pigs or poultry. Again, these should be expressed on a DM basis. Tables of feed composition and nutritive value are widely available, and these should be used to calculate the amount of energy provided by the feeds available.

However, the intake of feeds is not unlimited, and in order to obtain an accurate estimate of the contribution that feeds make in meeting the nutritional needs of livestock, it is necessary to include an adjustment to allow for variations in intake.

Despite the considerable research that has been undertaken to identify the factors that determine how much feed an animal will consume, experts do not agree on the mechanisms that control intake. It is clear, however, that a wide range of animal, feed and management characteristics influence intake, including:

- breed or strain of the animal/bird;
- age/weight;
- nutrient balance of the diet;
- accessibility to feed;
- health and welfare status;
- ambient temperature; and
- production level

19 This is the weight of feed after all moisture has been extracted.

In all livestock systems, the optimum feed intake will depend on the commercial goals of the enterprise within the constraints of the maximum potential intake of the animal or bird.

Where there is good access to feed, and health and welfare are optimum, then pigs and poultry would be expected to consume about 4–4.5 percent DM of their body weight per day as young stock, reducing to 3 percent of body weight in mature animals.

For ruminants, maximum DM intake is also likely to be 4 percent of body weight in young animals, declining to 2–2.5 percent in mature animals. However, where forages are the main or only feed, *voluntary* intake will be significantly influenced by the digestibility of the feed. Low digestibility feeds take longer to progress through the digestive tract, and as a result low digestibility is reflected in lower intakes.

In order to complete a feed balance, it is necessary to have an estimate of feed consumed, and the energy provided by it. However, predicting the intake of forages by ruminants has proved to be particularly challenging. A number of theories and equations have been developed to predict intake, many of them based on the digestibility of the forage, the amount of any supplementary feed, e.g. concentrate feeds, and the level of production. While they may be appropriate in many situations, an alternative approach for a feed balance is to use a form of reverse-balance calculation. Through this approach, the energy required for a given level of production – growth rate, milk yield, calves born etc. – is calculated. This is then divided by the energy concentration of the forage, after any energy provided by supplementary feeds has been discounted. This is illustrated below for a lactating dairy cow:

- Energy required for maintenance and production = 190 MJ ME/day
- ME provided by compound feed 1.8 kg DM at 12.5 MJ/kg DM = 22.5 MJ ME/day
- Energy from forages = 190 – 22.5 = 167.5 MJ/day
- ME content of forage = 10.5 MJ ME/kg DM
- Forage DM intake = 167.5/10.5 = 15.9 kg DM/day

In this example, dry matter intake is predicted as 15.9 kg/day but as discussed above it is necessary to allow for losses, and the estimate of the amount of feed required to sustain this level of production would need to be increased to adjust for these.

This approach can be used to calculate intakes on a daily basis for an individual animal, as illustrated above, but it can also be done for a herd of animals and on a monthly or annual basis. The choice will depend on the quality of the data available and the degree of precision required, although it should be noted that an annual estimate could lead to misleading conclusions where there is large seasonal variation in the amount of forage available. This approach can equally be used to make estimates of forage consumed on a regional or national basis, where data on the total output of milk or meat are available and the numbers of offspring produced are known. This approach is particularly appropriate for uniform categories of livestock such as lactating dairy cows or milking goats.

14.2.5 Reconciliation

Having established quantities of feed materials available and feed required by livestock, a surplus or deficit can be calculated. A surplus may suggest the potential for further livestock production, although it is important to establish when and where the surplus occurs. A surplus of forages during a brief period of the year or in an area not suitable to livestock production may not be fully utilizable unless livestock can be temporarily moved to the area. Alternatively, it may be possible to conserve the forage as silage or hay and used to supplement grassland when growth is low. In the case of a deficit, this can be rectified by increasing crop production or improving the efficiency of conservation of surplus forages by the purchase of feeds or a reduction in numbers of animals.

Feed deficits may be covered by feed imports. However, feed importation is not without environmental consequences. Although increased imports can sustain more animals, the increased numbers of animals may also increase grazing pressures on pastures and rangelands. Increased feed import also results in increased animal waste material and associated nutrients that must be appropriately managed.

As in the case of India, computed feed balances may indicate growing feed deficits despite counter evidence that livestock productivities have increased (see Chapter 9). Such discrepencies may point to increased reliance on feed resources that are important but overlooked or underestimated in feed inventories. Examples might include crop residues, industrial by-products, roadside vegetation, fallen tree leaves, seedpods that have fallen or been shaken down from trees, cut tree branches and other poorly quantified, but increasingly important feed resources in feed deficit situations arising from high livestock densities, intensive land uses, drought or severe winter weather.

Although a feed balance can be assessed at a national level, greater accuracy will be achieved if it is done at local or regional levels and the results consolidated. Because of the different feeds for ruminant and non-ruminant livestock, it is recommended that reconciliations are done separately for each species before producing a national feed balance.

14.3 REFERENCES

The following is a list of a number of national publications providing data on nutrient requirements and feed composition for livestock. In addition, livestock breeding companies frequently publish tables on nutrient requirements for specific breeds and strains of livestock.

AFRC. 1993. *Energy and protein requirements of ruminants.* An advisory manual prepared by the AFRC Technical Committee on Responses to Nutrients. CAB International, Wallingford, UK

ARC. 1980. *The nutrient requirements of ruminant livestock*. Commonwealth Agricultural Bureaux, Farnham Royal, UK.

CSIRO. 2007. *Nutrient requirements of domesticated ruminants*. CSIRO Publishing, Collingwood, Australia.

INRA. 1978. *Alimentation des ruminants* (Ed. R Jarrige). INRA Publications, Versailles, France.

NRC. 1985. *Nutrient requirements of sheep* (6th edition). National Research Council. National Academy Press, Washington, DC, USA.

NRC. 1998. *Nutrient requirements of swine* (10^{th} Revised edition). National Research Council. National Academy Press: Washington, DC, USA.

NRC. 2001. *Nutrient requirements of dairy cattle* (7th Revised edition). National Research Council. National Academy Press: Washington, DC, USA.

NRC. 2006. *Nutrient requirements of small ruminants*. National Research Council National Academy Press, Washington, DC, USA.

15. The use of ecosystem simulation modelling to assess feed availabilities for large herbivores in heterogeneous landscapes

Michael Coughenour
Natural Resource Ecology Laboratory, Colorado State University, Fort Collins, Colorado, USA
Email: mikec@nrel.colostate.edu

15.1 INTRODUCTION

Arguably, the problem of assessing feed availability for livestock on spatially extensive grasslands and rangelands is essentially the same as assessing sustainable carrying capacity for large herbivores in heterogeneous landscapes. The primary objective of both is the same, to determine how many animals can be sustained by accessible forage and water. This in turn determines the amount of secondary production the livestock can provide to humans. Ecosystem modelling has been used to assess carrying capacities and it could likewise be used to assess feed availabilities.

There are many definitions of carrying capacity, but one would be that at carrying capacity, herbivores should not diminish the capacity of soils, vegetation and fauna to function together as an ecosystem. So defined, carrying capacity appears to be a straightforward concept. However, the task of defining what carrying capacity is exactly, and agreeing upon a method for calculating its value, is not easy. Definitions vary with management objectives, for example managing for maximum productivity, natural processes, or multiple and often conflicting uses of rangelands. More fundamental challenges arise due to the difficulty of calculating forage availability in temporally variable and spatially heterogeneous environments. Although remote-sensing data and GIS have enabled assessments of total vegetation productivity across space and time, additional complications arise concerning the consequences of that productivity for herbivores. Furthermore, herbivores affect numerous ecosystem processes through dynamic and interactive effects on plant growth, plant competition, nutrient cycling, organic matter decomposition, flows of water through plants and soil, competition or facilitation of other herbivores, and predation. These effects feed back onto the plants and herbivores at the ecosystem level of organization. Thus, an ecosystem approach is necessary to assess the effects of herbivory in the context of dynamic and spatially heterogenous landscapes.

There are substantial challenges in assessing feed availability on spatially extensive grasslands and rangelands. It is difficult to estimate feed availability simply by summing up total plant biomass, much less total green plant matter or even net aboveground primary production. The first challenge is temporal variability. Biomass availability fluctuates seasonally due to precipitation and snow cover. As a result, herbivores may be highly limited by the durations of low biomass availability. Forage quality also varies seasonally. Although green plants may constitute good forage, the same plants may provide little nutrition or be inedible when senescent. Second, forage quality varies among species. Some species are chemically or physically defended, or are avoided by herbivores for other reasons. Third, the fraction of total plant biomass or primary production that is accessible or usable by herbivores varies spatially. Plant biomass may be unavailable due to lack of nearby drinking water, snow cover, inaccessible topography, competition with wildlife and barriers such as fencing. As a result of these temporal and spatial constraints on forage availabilty, herbivore densities are often considerably lower than would be predicted on the basis of total plant biomass. In northern Kenya, for example, less than 10 percent of forage was consumed by pastoral livestock, yet forage was still a limiting factor to livestock densities (Coughenour *et al.,* 1985).

Herbivore populations are often limited by the amount of forage that is available on a limited portion of the landscape during dry seasons and winters. In many pastoral grazing systems, there are "dry season grazing reserves". These are often areas that are less desirable to use during the growing season for some reason, such as overly warm temperatures at lower elevations, long distances to water or difficult topography. In northern Kenya, for example, livestock populations were limited to forage in locations that were little used during wet seasons (Swift *et al.,* 1996), which is why a small fraction of the forage in the whole system was consumed and why the herbivore population was smaller than might be expected given the apparent abundance of forage during the wet season (Coughenour *et al.,* 1985; Ellis and Swift, 1988). Limiting areas of this sort have been termed "key resource areas" (KRAs) (Ilius and O'Conner, 1999, 2000).

Ecosystem modelling is a powerful approach to assessing herbivores in ecosystems, both with respect to their responses to forage and other resources as well as their effects on vegetation and other ecosystem components. Several features of this approach make this possible. First, such models represent processes and outcomes of those processes as related to flows of biomass, nutrients, water and energy among soils, decomposers, plants, herbivores and the atmosphere. These flows include those which determine forage production and forage utilization by herbivores. Second, such models are dynamic. They represent important variations in time, among seasons and among years, as driven by fluctuations in temporally varying driving variables, particularly weather. Variances between wet and dry seasons, and warm and cold seasons all affect forage availability to herbivores. The durations and frequencies of food shortages are critical determinants of net outcomes for herbivores. Third, it is possible for such models to represent spatial heterogeneity. The spatial distributions of forage and water determine their availabilities, inasmuch as the spatial distributions of herbivores in space and time must intersect with the spatial distributions of these two critical resources. Fourth, models can be used to assess ranges of possible outcomes for herbivores due to ranges of variation in weather and management. Instead of a single number for forage supply, a range of outcomes might be anticipated. Fifth, issues of sustainability can be addressed at the ecosystem level. This entails continued viability of the entire food production system, inclusive of ecosystem services and biodiversity.

The objective here is to illustrate the ecosystem modelling approach by describing the application of such a model to assess an ecosystem supporting a population of large herbivores in western North America. A brief case study of the application of the model to a free-ranging horse population in the Pryor Mountain Wild Horse Range (Coughenour, 1999) shows the potential of ecosystem modelling to assess feed availabilities in spatially extensive grasslands and rangelands characterized by temporal variability and spatial heterogeneity.

15.2 THE ECOSYSTEM MODEL

SAVANNA is a spatially explicit, process-oriented, multi-species model of grassland, shrubland, savanna and forested ecosystems. It was first developed to represent a spatially extensive pastoral ecosystem in northern Kenya (Coughenour, 1992). The model has since been applied to a wide variety of ecosystems (e.g. Boone *et al.,* 2002, 2004, 2005; Boone, 2005; Christensen *et al.,* 2003; Coughenour, 1999, 2002, 2005; Kiker, 1998; Leidloff *et. al.,* 2001; Ludwig *et al.,* 2001; Weisberg *et al.,* 2002, 2006). SAVANNA is an integrated modelling aproach, paying equal attention to animals, plants and their interactions (Weisberg *et al.,* 2003). The overall structure of the model is shown in Figure 15.1. Details and applications of the model can be found at www.nrel.colostate.edu/projects/savanna/.

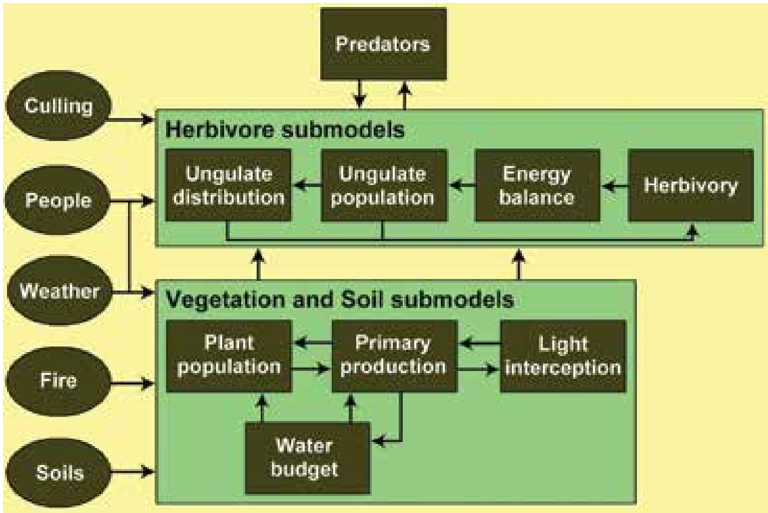
The spatial structure is a mosaic of grid-cells that covers landscapes or regional-scale ecosystems (Figure 15.2). Primary spatial inputs include GIS layers representing: 1) weather; 2) topography; 3) vegetation types and attributes; 4) herbaceous biomass; 5) woody cover and sizes; 6) soil types and attributes; 7) herbivore range maps, 8) distance to water; 8) fires. Animals, water, and fire can "move" across the landscape in the model. In order to carry out simulations in a reasonable time frame on workstation class computers, the total number of grid-cells is limited to between 10 000–100 000. Thus, when larger study areas are simulated, grid-cells must be larger. The model runs on a weekly time step, which is sufficient for capturing critical intra-annual and seasonal dynamics, but much less demanding than a daily time step. The model is normally run for 10–100 year time spans.

Monthly or weekly weather data from all stations in the study area are read into the model. The model computes precipitation and temperature maps from the point data as it is running, using elevation corrected spatial interpolation. A water balance model simulates soil moisture in three layers.

The site water balance submodel simulates soil moisture dynamics and use on each patch type on each grid cell. A soil map is used in conjunction with soil properties for each soil type to determine soil water holding capacities of each subarea. Water is routed to three soil layers using a simple "tipping bucket" approach that drains water in excess of field capacity to deeper layers. The water budget includes terms for precipitation, interception, runoff, runon, infiltration, deep drainage, bare soil evaporation and transpiration. Transpiration is an outcome of stomatal conductance, leaf area, humidity and radiation.

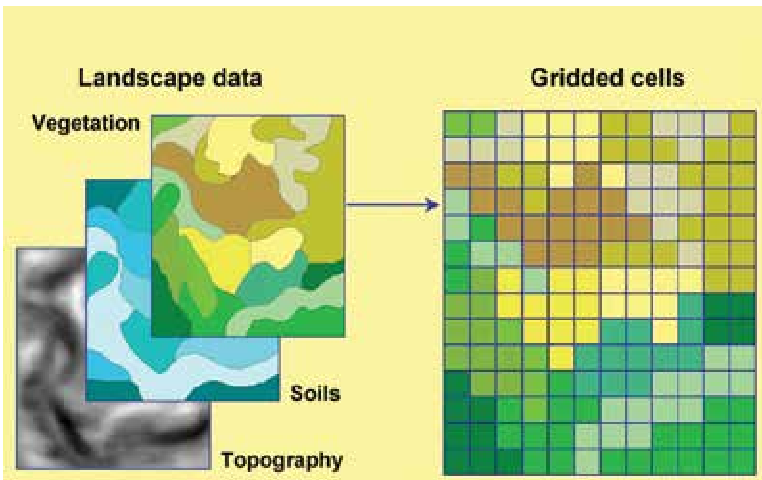
Snow water content is simulated by adding to the snow pack when there is precipitation with temperatures below freezing, and melting from the snow pack based on temperature and solar radiation. Snow depth is derived from snow water content. Increasing snow depths impedes herbivore forage intake rates. Because precipitation and temperature vary with location and elevation, snow depths also vary with location and elevation.

FIGURE 15.1
SAVANNA model structure



Source: R. Boone (graphics)

FIGURE 15.2
SAVANNA spatial structure



Source: R. Boone (graphics)

Normally 3–10 plant functional groups are simulated, where functional groups are usually defined in terms of life form (herb, shrub, tree), leaf longevity (deciduous, evergreen) and palatability. Plant biomass, functional group composition and woody cover are initialized on the basis of a vegetation map and a corresponding lookup table linking vegetation type to these attributes.

The net primary production (NPP) submodel simulates plant biomass flows and dynamics. Photosynthesis is modelled as a function of light, temperature, soil moisture, and plant nitrogen content. Respiration is separated into growth and maintenance components. Herbaceous NPP is allocated to leaves, stems and roots. Woody plants allocate NPP to leaves, fine branch, coarse branch, fine root and coarse root. Water demands are derived from the transpiration calculation. Nitrogen (N) demands are calculated based on the concentration of inorganic soil N. Root water and N uptakes to supply demands are allocated among soil layers in proportion to the products of available resources and root biomass in each layer. Predictions of plant biomass dynamics and primary production have compared favorably with available data in every application of SAVANNA. In most cases, available data at least include peak biomass over 3–5 years (e.g. Coughenour, 2005). Ideally, data for intraseasonal dynamics of live and dead biomass are used (e.g. Coughenour, 1999).

The woody plant population submodel simulates plant establishment, size and mortality in six age classes of aboveground stems. The sizes of stems in each age class are determined by growth histories, including exposure to fire and herbivory. Allocation of NPP in woody plants is tied to plant size through allometric relationships. The model represents woody plant morphometrics (dimensions and biomass) for six size classes of plants. These include dimensions for crown diameter, stem diameter, height and rooting zone area or the root biomass density per square meter of soil. Biomass values are specified for leaves, fine branches, coarse branches, coarse roots and fine roots for each of the size classes.

A decomposition and N-cycling submodel based on CENTURY[20] (Parton *et al.,* 1987, 1998), simulates litter breakdown and the formation and turnover of soil organic matter (SOM). Decomposition and mineralization rates are affected by temperature and soil moisture. The CENTURY decomposition model is quite general, and has been validated in many different environments globally. Soil carbon and nitrogen values are initialized by soil types on the input soil map.

The herbivore models simulate multiple animal species or functional groups. Each species or group is modelled individually, with separate parameters describing body size, energy requirements, foraging, demography, and so on. Herbivore forage intake is predicted as a function of animal body size, forage biomass (the functional response), and forage quality (due to decreased rate of passage in ruminants at low quality). Body size and digestive physiology effects on forage intake rate and forage quality are explicitly included. A diet selection submodel distributes herbivory among plant types and tissues using dietary preference weights.

The energy balance of the animal is a simulated outcome of energy intake and expenditure. An animal condition index is derived from resultant body weight gains and losses. Energy intake depends on forage biomass intake and forage energy content. Energy requirements can be expressed in terms of the digestible energy (DE), metabolizable energy (ME) or net energy (NE). The fraction of the gross energy content of forage that is undigestible is excreted as faeces. The DE fraction is the energy that is actually digested. Of the

[20] The CENTURY model is a general model of plant-soil nutrient cycling which is being used to simulate carbon and nutrient dynamics for different types of ecosystems including grasslands, agricultural lands, forests and savannas.

amount digested, some is lost to urine and, in ruminants, to fermentation gases (methane) produced by rumen microbes. The energy left after these losses is the ME, which is used for maintenance, weight gain, gestation and lactation. Additional costs of walking and other activities can also be considered.

Herbivores are dynamically distributed in space using a dynamic habitat suitability index (HSI) model that dynamically distributes animals in proportion to the distribution of HSI, which is in turn computed from the potential rate of energy intake, green forage biomass, topography, woody cover and distance to water. The HSI formulation can be heuristically based upon known habitat preferences and logistic regression. Recently, Mahalanobis distance weighting[21] has been used (de Knegt *et al.,* 2010). Seasonal migrations are modelled by designating the seasonal ranges and making movements among ranges dependent on relative habitat conditions.

15.3 CASE STUDY

15.3.1 Study area

The Pryor Mountain Wild Horse Range (PMWHR) is located on the border between Montana and Wyoming, east of Yellowstone National Park. The PMWHR landscape is topographically diverse, with elevations ranging from 1 200 to 2 400 m. As a result of this elevation gradient, climatic conditions vary markedly with respect to temperature, precipitation and snow conditions. A complex and active geologic history has created a high diversity of geological substrates, including limestones, sandstones, shales, siltstones and granites. The vegetation of the PMWHR is diverse (Figure 15.3), primarily due to the large elevation and associated climatic gradient, but also due to the wide variety of soils and substrates and patterns of water redistribution on the landscape. Desert shrubland occurs at the lowest elevations (<1 200 m), sagebrush steppe occurs at 1 200–1 600 m, juniper/mountain mahogany shrublands and woodlands occur on very shallow soils at 1 100–1 550 m elevations, and coniferous forests occur at higher elevations above 1 600 m. An early census taken in 1970 prior to any removals totaled 270 horses. Numbers were reduced to the 100–120 range in the 1970s–80s through to the present. The range is shared with bighorn sheep, and mule deer and horse competition for forage with the bighorn sheep has been a concern.

15.3.2 Model implementation

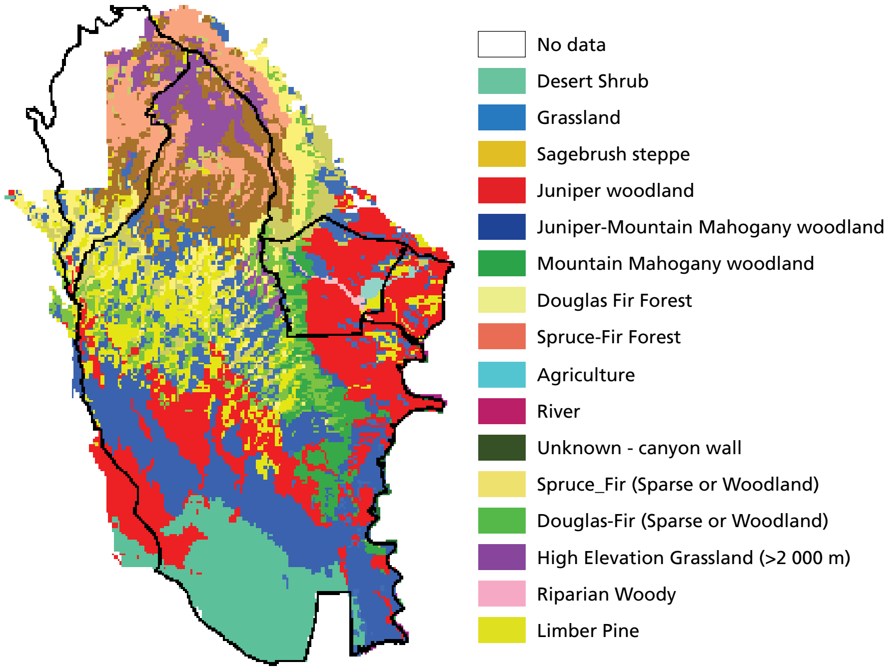
The model was parameterized and input data sets were developed for the study site. The objective was to use the model to simulate historic and current scenarios of vegetation and herbivore management. The model would be used to estimate herbivory effects on vegetation and soils, and herbivore population responses to alternative management policies.

Six functional groups of plants were simulated; grasses, forbs, shrubs, mountain mahogany (*Cercocarpus*), juniper and coniferous tree. These groups were chosen to meet the objectives of this modelling analysis without making the model overly complex.

Three horse herds were modelled and limited to observed seasonal ranges. Seasonal

[21] Mahalanobis distance weighting is a procedure that measures the relative suitability of a habitat with respect to the known preferences of a species for multiple habitat variables.

FIGURE 15.3
Vegetation heterogeneity on the PMWHR

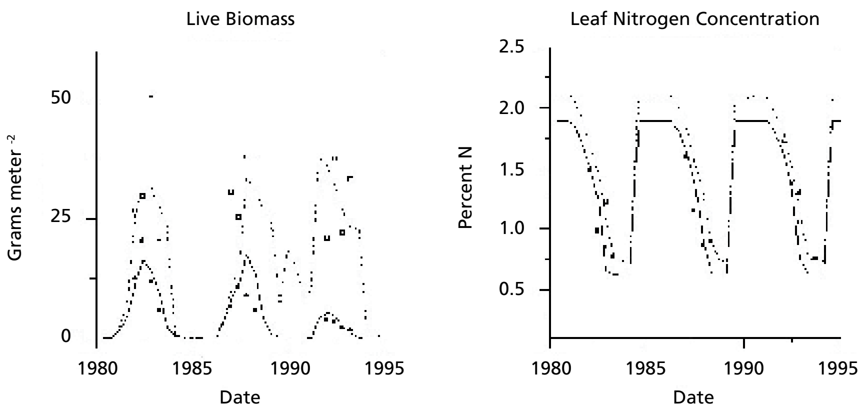


movements were modelled as dynamic responses to changing forage and snow conditions, with a seasonal avoidance of low elevations in summer. Habitat suitability increased with forage biomass and forage energy intake rate. Horses were assumed to prefer areas with moderate topography. Water is a major determinant of horse distributions during the spring, summer and autumn, while snow is available to horses during winter, allowing horses to use virtually all of the horse range. The model was parameterized so that there was a high preference for water less than 1.5 km distant, declining with greater distances so that areas beyond 6 km of water were considered unuseable.

Bighorn sheep were kept within observed seasonal ranges and redistributed within the ranges in relation to forage biomass, forage energy intake rate and topography (escape terrain). Mule deer were present during the winter and had access to the entire landscape, but avoided steep slopes.

The capability of the model to predict herbaceous shoot biomass and leaf nitrogen dynamics was tested through comparisons of simulated results with field data for plant biomass dynamics (Detling *et al.,* 1996). Optimally, a dynamic model such as this one, which aims to simulate seasonal dynamics, is tested against data which show these dynamics. Furthermore, to assess total productivity and grazing impacts on vegetation, grazing exclosures need to be employed. Data were taken inside and outside of each exclosure. Live and dead shoots of grasses and forbs were measured, along with leaf N concentrations. An example comparison of simulated and observed data at one exclosure is shown in Figure 15.4.

FIGURE 15.4
Comparison of simulated (lines) and observed (points) data at one exclosure site



Note:
Solid lines and filled points – grasses.
Dashed lines and open points – forbs.

15.3.3 Example results

The main purpose here is illustrate the types of outputs that are provided by this type of model. It is necessary to examine graphical outputs that show both temporal dynamics and spatial heterogeneity to reveal the capability to address the major challenges of assessing feed availabilty in spatially extensive grasslands and rangelands.

With respect to temporal variations, Figure 15.5 shows the temporal dynamics of herbaceous biomass over three decades. The important features to note are the magnitudes of the inter-seasonal and inter-annual fluctuations, which are significant determinants of feed availability. Figure 15.6 shows the temporal responses of forage intake rate to feed availability, as affected by biomass, snow cover and animal locations. Figure 15.7 illustrates the resultant dynamics of animal condition in response to fluctuations in forage availability and intake rates.

With respect to spatial heterogeneity, Figure 15.8 exemplifies model predictions of the distribution of potential forage biomass across the landscape, in terms of net annual primary production (NAPP). Figure 15.9 shows the predicted spatial distributions of horses year-long. Figure 15.10 then shows the combined results of animal distributions and plant growth distributions for percent offtake.

15.4 CONCLUSIONS

The application of a spatially explicit ecosystem model to a landscape in North America inhabited by free-ranging herbivores illustrates both the challenges of assessing feed availabilities in spatially extensive grasslands and rangelands, and the potential of the ecosystem modelling approach to address these challenges. The model has been applied to similar situations elsewhere.

FIGURE 15.5
Temporal variations in grass and forb biomass

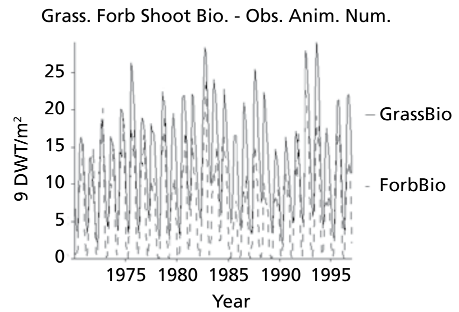


FIGURE 15.6
Temporal variations in forage intake rate in response to fluctuations in feed availability

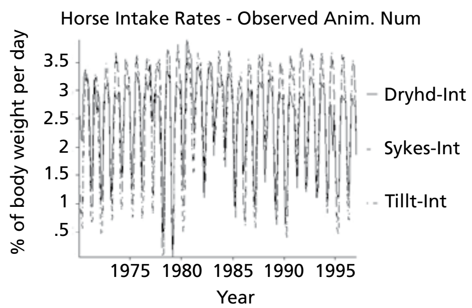


FIGURE 15.7
Responses of animal condition index to variations in feed intake

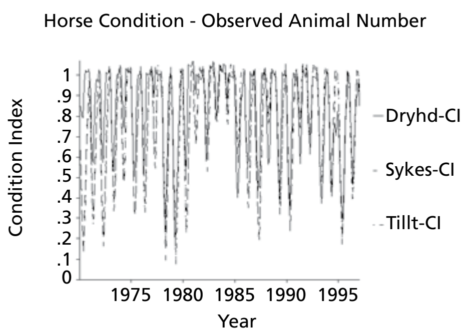


FIGURE 15.8
Spatial distribution of aboveground net primary production (ANPP)

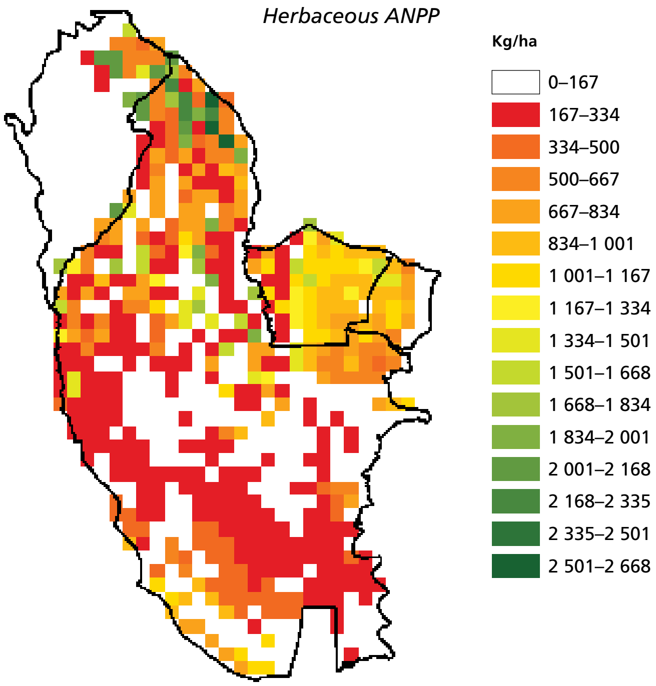


FIGURE 15.9
Spatial distribution of horse densities year-long

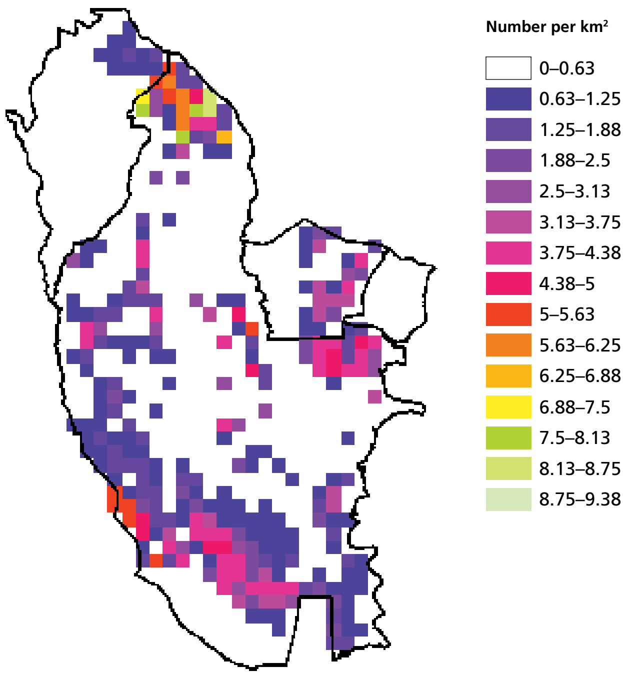
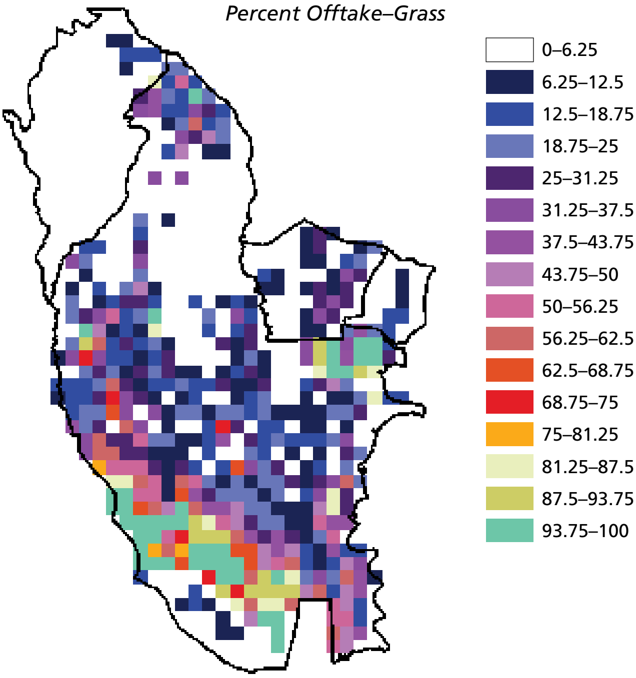


FIGURE 15.10
Spatial distribution of percent offtake of grass productivity, a net outcome of the spatial distributions of plant growth and horses



Feed availability was assessed, first of all, by predicting plant production and biomass dynamics based on weather, soil properties, and vegetation composition and cover. Plant growth was tightly linked with soil water balance, which is particularly important in water-limited grasslands and rangelands. Seasonal and inter-annual fluctuations in plant biomass quantity and quality were predicted as a result of corresponding variations in precipitation and temperature. Temporal variations included variations in live versus senses-cent biomass, and variations in tissue nitrogen and digestible energy contents. The spatial distributions of plant growth were outcomes of the spatial distributions of weather and soil properties. Precipitation and temperature maps generated from spatial interpolation, along with soil properties, were the principle driving variables for temporal and spatial variations in plant productivity.

The problem of there being multiple plant types with varied values for herbivores was addressed by simulating multiple plant functional groups. Herbaceous plants were distin-guished from woody plants, which is of major significance in distinguishing feeds available to grazing versus browsing herbivores. Futhermore, leaf biomass of woody plants may have been out of reach of browsing herbivores due to height above the ground, which is simulated by virtue of woody plant sizes.

Availabilities were also predicted to be constrained by the overlaps of simulated animal distributions with simulated plant biomass distributions. Animal distributions were con-strained by distance to water, topography and snow, and they were affected by animal selectivities for areas with greater forage quantity and quality. The juxtaposition of plant and animal distributions in time determined foraging opportunities, with subsequent impacts on forage intake rates.

The simulation of animal energy balance was central to predicting potential animal production responses to feed availability. In the context of this document, this has significant implications for assessments of the consequences of feed availability for livestock production. What the model accomplishes is essentially equivalent to a dynamic calculation of feed balance, the balance between animal nutritional intake versus requirements. Here, the feed balance was affected by spatial and temporal variations in feed availability, which in turn was affected by many environmental variables, including vegetation, topographic and snow cover variations.

The concept of key resource areas was addressed by simulating the temporal and spatial variations in forage quantity and quality just described. As dry seasons progress, or as winter conditions deteriorate, actual "forage" – as opposed to biomass – becomes increasingly limited in its spatial extent to areas with soil moisture reserves, areas that have not been grazed yet, and areas that are otherwise located in less desirable locations due to topography, distance from water or other factors. The spatial extents of these areas vary in the model inasmuch as the spatial extents of simulated resources (especially soil moisture) vary spatially and temporally.

Although the technological and data demands on the ecosystem modelling approach are currently daunting, ultimately it will become feasible to implement this approach quite readily. Data availability is increasing due to advances in remote-sensing and GIS capabilities. Computational limitations continue to be be lifted with hardware advances. What is most limiting is modelling expertise.

15.5 REFERENCES

Boone, R.B. 2005. Quantifying changes in vegetation in shrinking grazing areas in Africa. *Cons. Soc.*, 3: 150–173.

Boone, R.B., Coughenour, M.B. Galvin, K.A. & Ellis, J.E. 2002. Addressing management questions for Ngorongoro Conservation Area using the Savanna Modelling System. *African J. Ecol.*, 40: 138–150.

Boone, R.B., Galvin, K.A., Coughenour, M.B., Hudson, J.W., Weisberg, P.J., Vogel, C.H., & Ellis, J.E. 2004. Ecosystem modelling adds value to a South African climate forecast. *Clim. Change*, 64(3): 317–340.

Boone, R.B., Burnsilver, S.B., Thornton, P.K., Worden, J.S., & Galvin, K.A.. 2005 Quantifying declines in livestock due to subdivision. *Rangeland Ecol. Manag.* 58: 523–532.

Christensen, L., Coughenour, M., Ellis, J., & Chen, Z. 2003. Sustainability of the Typical Steppe: Model Assessment of Grazing on Ecosystem State. *J. Range Manag.*, 5: 319–327.

Coughenour, M.B. 1992. Spatial modelling and landscape characterization of an African pastoral ecosystem: a prototype model and its potential use for monitoring drought. *In* D.H. McKenzie, D.E. Hyatt & V.J. McDonald, eds. *Ecological Indicators Vol. I*. Elsevier Applied Science, London and New York, pp. 787–810.

Coughenour, M.B. 1999. *Ecosystem modelling of the Pryor Mountain Wild Horse Range.* Report to USGS. Biological Resources Division, National Park Service, and Bureau of Land Management. 55 pp. & 100 figures.

Coughenour, M.B. 2002. *Elk in the Rocky Mountain National Park Ecosystem – A Model-Based Assessment.* Final Report to USGS Biological Resources Division, Ft. Collins, Colorado and U.S. National Park Service, Rocky Mountain National Park. 125 pp. & 116 figures.

Coughenour, M.B. 2005. *Spatial modelling of Yellowstone Bison and their environments.* Final Report to U.S. Geological Survey, Biological Resources Division, Bozeman, MT. Three-part report. 93 pp., 100 figures, 73 tables.

Coughenour, M. B., Ellis, J. E., Swift, D. M., Coppock, D.L., Galvin, K., McCabe, J.T. & Hart, T.C. 1985. Energy extraction and use in a nomadic pastoral ecosystem. *Science,* 230: 619–624.

Detling, J.K. & Gerhardt, T. 1996. *Monitoring vegetation in the Pryor Mountain Wild Horse Range*. Second Annual Report. Colorado State University, USA.

Ellis, J.E., & Swift, D.M.1988. Stability of African pastoral ecosystems: alternative paradigms and implications for development. *J. Range Manag.,* 41: 450–459.

Kiker, G.A. 1998. *Development and comparison of Savanna ecosystem models to explore the concept of carrying capacity*. Cornell University, Ithaca, New York, USA. Ph.D. Thesis.

De Knegt, H.J., van Langevelde, F. van, Coughenour, M., Skidmore, A., de Boer, W., Ieitkonig, I., Knox, N., Kohi, E., Peel, M., Slowtow, R., van der Waal, C., van Wieren, S., & Prins, H. 2010. Spatial autocorrelation and the scaling of species-environment associations. Ecol. 91: 2455–2465.

Illius, A., & O'Conner, T. G. 1999. The relevance of non-equilibrium concepts to arid and semi-arid grazing systems. *Ecol. Appl.,* 9: 798–813.

Ilius, A.W. & O'Connor, T.G. 2000. Resource heterogeneity and ungulate population dynamics. *Oikos,* 89: 283–294.

Liedloff, A.C., Coughenour, M.B., Ludwig, J.A., & Dyer, R. 2001. Modelling the trade-off between fire and grazing in a tropical savanna landscape, northern Australia. *Environ. Int.,* 27: 173–180.

Ludwig, J. A., Coughenour, M. B., Liedloff, A.C., & Dyer, R. 2001. Modelling the resilience of Australian savanna systems to grazing impacts. *Environ. Int.,* 27: 167–172.

Parton, W.J., Schimel, D.S., Cole, C.V., & Ojima, D.S. 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. *Soil Sci. Soc. Am. J.,* 51: 1173–1179.

Parton, W., Hartman, M., Ojima, D., & Schimel, D. 1998. DAYCENT and its land surface submodel: description and testing. *Global Planetary Change,* 19: 35–48.

Swift, D.M., Coughenour, M.B. & Atsedu, M. 1996. Arid and semiarid ecosystems. Chapter 10 *In*: *East African ecosystems and their conservation*. Oxford University Press, New York, USA.

Weisberg, P., Hobbs, N.T., Ellis, J. & Coughenour, M. 2002. An ecosystem approach to population management: alternatives for managing elk on ranges shared with cattle. *J. Environ. Manag.,* 65:181–197.

Weisberg, P. & Coughenour, M. 2003. Model-based assessment of aspen responses to elk herbivory in Rocky Mountain National Park, U.S.A. *J. Environ. Manag.,* 32: 152–169.

Weisberg, P.J., Coughenour, M.B. & Bugmann, H. 2006. Modelling of large herbivore-vegetation interactions in a landscape context. Chapter 12. *In* K. Danell, R. Bergstrom, P. Duncan & J. Pastor, eds. *Large herbivore ecology, ecosystem dynamics and conservation.* Cambridge University Press, Cambridge, UK.

16. Technologies, tools and methodologies for forage evaluation in grasslands and rangelands

Jay P. Angerer
Texas A&M University System, Blackland Research and Extension Center, 720 E. Blackland Road, Temple, TX 76502-9622, USA
Email: jangerer@brc.tamus.edu

16.1 INTRODUCTION

With changing climate, increasing human population and changes in land cover/land use, a comprehensive quantification of livestock feeds is needed at national level in order for countries to develop policies for maintaining or increasing livestock production. This information can also be used for feed and livestock management in the case of drought or other disasters. For many developing countries, grassland and rangeland vegetation comprise a large component of the feed that is potentially available for livestock use. Worldwide, rangelands occupy almost 50 percent of the terrestrial land cover, and provide almost 75 percent of the forage used by domestic livestock (Brown and Thorpe, 2008). Moreover, livestock production from grasslands and rangelands can be a significant contribution to the overall gross domestic product (GDP) in developing countries. However, because of the generally large land areas occupied by grasslands and rangelands, their remote locations and the diverse mix of livestock species that graze these lands, quantification of vegetation biomass for feed inventories can be challenging.

For grasslands and rangelands, the amount or quantity of forage biomass is not the only important factor influencing livestock production. An assessment of forage quality is also needed because this influences the forage intake of grazing animals and ultimately animal performance. Forages that are in large quantity but have low quality can reduce animal performance or not be utilized because the forage is not palatable to the grazing animals. Forage quality can vary seasonally with topography and with changing plant communities across the landscape (Wofford *et al.*, 1985). Measuring forage quality poses challenges because of selective grazing by livestock (i.e. in a mix of plant species, the animal selects the plants it prefers to eat) and the ability of animals to graze across large distances, thus potentially encountering multiple plant species/communities and topographic positions along the way.

For both forage quantity and quality assessments, an array of methods has been developed for measurement that vary in level of accuracy, time spent in the field and logistical implementation. For forage quantity measurements, methods include direct measurements of vegetation, estimation with proxy variables, simulation modelling, or various combinations of these methods. For forage quality measurement, direct and indirect methods are available in addition to nutritional balancing and least-cost ration software for use in devising supplemental feeding strategies.

Logistics, costs, timing of data collection and available personnel each influence the choice of method. The purpose of this review is to provide an overview of the technologies, tools and methodologies that are currently available for forage quantity and quality evaluation in grasslands and rangelands that can be used for national feed inventories. Methods using field-based techniques, remote sensing, simulation models and decision-support tools for assessments of forage quality and quantity are reviewed, and advantages and disadvantages as they relate to national feed inventories are discussed. Factors such as distance to water and terrain that influence forage availability are reviewed and examples given on how this information can be used in assessing forage usability and in calculating stocking rates. In order for a national feed inventory programme to be able to deliver timely and geographically relevant data to stakeholders, data management, storage, quality control and integration need to be considered. A general overview of these requirements is also be provided.

16.2 OVERVIEW

16.2.1 Field techniques for assessing and monitoring forage quantity and quality

Field techniques are the most accurate methods for assessing forage quality and quantity on rangelands. However, field techniques generally require a large amount of time and resources for data collection, especially if data are needed on a yearly basis. Logistics, costs, timing of data collection, available personnel, type of grazing animal and plant community each influence the choice of method. An overview of some of the more widely used techniques for forage quantity and forage quality assessments is presented below.

16.2.2 Forage quantity assessment

A major consideration in assessing forage quantity for a national feed inventory on rangelands and grasslands is to define the vegetation biomass that will be measured to represent the inventoried "feed". Because grazing animals consume vegetation based on their preference for particular species in a mix of plants on the landscape, the biomass to be measured in the field should reflect the biomass that is generally grazed by the animal of interest. The aboveground vegetation biomass that is produced by all plant species at a given site during a single growing year can be defined as *total annual production* (Herrick *et al.*, 2005). However, total annual production does not reflect the availability or the palatability of the biomass to the grazing animal. *Total annual forage production* can be defined as the aboveground biomass from the plant species that is likely to be consumed by the grazing animals (Herrick *et al.*, 2005). The quantity of total annual forage production can be quite different for a given site depending on the grazing animal. For example, on a grass-dominated site, total annual forage production is greater for a cow than for a goat because cattle generally prefer to consume grasses rather than shrub vegetation (Photo 16.1). The opposite is true on a shrub-dominated site, because goats tend to prefer to browse trees and shrubs compared with herbaceous vegetation (Photo 16.1). In addition, availability of forage to the grazing animal must be considered. Plants that are too tall or inaccessible to the grazing animal should not be included in the inventory. Therefore, prior to field data collection for a forage quantity assessment, the grazing animals of concern must be identified in order to develop a sampling protocol that considers the plant species that are consumed by the livestock and the availability of those plants to the grazing animal (USDA, 2003).

Time of year for the forage quantity assessment is another major consideration. The productivity of plants at a given site or across regions can vary throughout the year due to variations in plant species growth cycles and due to climatic variability (Herrick *et al.*, 2005). Generally, the inventory should be conducted when the majority of plant species under consideration are at peak biomass. At the time of sampling, the measured biomass may require adjustments to reflect biomass that has already been removed by grazing animals or that has not yet been produced (USDA, 2003).

Methods for biomass measurement include direct measurement techniques where biomass is sampled and weighed, estimation techniques where the weights are estimated by the observer, or a combination of these methods.

16.2.3 Direct measurement techniques

One of the most common methods for direct measurement of forage production on grasslands and rangelands is the quadrat method. A quadrat is a circular, square or rectangular frame of a known area that is placed on the ground and the vegetation biomass within the quadrate frame can be clipped and removed for weighing (Photo 16.2). For herbaceous plants (grasses, grass-like plants and forbs), aboveground plant parts such as leaves, stems, inflorescenses and fruit are clipped/removed from within the quadrat (USDA, 2003). For woody trees and shrubs, only the current year's growth (leaves, twigs, fruits) is sampled within the quadrat. However, Catchpole and Wheeler (1992) caution that quadrat sampling for trees and large shrubs may not be practical where spatial variability is high, and that other techniques such as estimation may be more useful.

Photo 16.1
When grazing, cattle generally prefer to graze grass or herbaceous vegetation (top) while goats prefer to graze trees and shrubs (bottom)

After clipping, samples are usually oven-dried to remove water so that biomass can be expressed on a dry matter basis. Since the area of the quadrat is known (e.g. 0.5 m^2), the dry weight (e.g. kg) of the biomass can then be extrapolated to a larger areas (e.g. kg of biomass/ha) to obtain an estimate of vegetation biomass for the site of interest. Prior to clipping, the vegetation within the quadrat may also be evaluated for other important vegetation characteristics such as plant species composition, cover, frequency and litter biomass.

Transect lines can be used to assist in establishing a baseline from which quadrat sampling can occur (Photo 16.3). The transect start and end points can be georeferenced with a Global Positioning System (GPS) so that the transect can be located again in subsequent visits to the site for long-term monitoring and for assessing vegetation and productivity changes.

The length of the transect, size and shape of the quadrat used, and the number of transects and quadrat samples collected for measuring vegetation biomass at a site of interest depends on several factors. These include the lifeform of the vegetation (e.g. tree, shrub, forb or grass), the spatial distribution of the vegetation on the landscape (e.g. sparse or dense) and the logistics of collecting data at the site. For example, smaller quadrats (0.1 to 1.0 m^2) can be used to sample herbaceous vegetation like grasses and forbs. Larger quadrats (2.0 to 500 m^2) can be used to sample shrubs and trees. For clumped or patchy vegetation, a long rectangular quadrat is recommended to reduce bias in sampling clumps versus bare ground. The number of quadrats required to sample a specific site is related to the size of the quadrat, but also depends on the vegetation type, spatial variability and, ultimately, the logistics and costs of sampling the area of interest. The greater the

Photo 16.2

A 0.5m^2 quadrat used for measuring vegetation biomass on rangeland vegetation

NOTE: VEGETATION WITHIN THE QUADRAT IS CLIPPED AND PLACED IN A PAPER SACK THAT IS MARKED WITH SAMPLE PLOT INFORMATION; AFTER CLIPPING, THE BAG IS TAKEN TO THE LABORATORY, DRIED AND WEIGHED TO OBTAIN DRY MATTER WEIGHT.

spatial variability of the vegetation, the greater the number of quadrats samples needed to increase precision of the biomass measurements (Catchpole and Wheeler, 1992). Statistical techniques for calculating sample size can be used to assist with determining the optimum number of samples. Bonham (1989) provides a description of techniques and procedures that can be employed to determine optimal quadrat size and number of quadrat samples needed for various vegetation types.

16.2.4 Estimation techniques

The time required for clipping a larger number of quadrats and the large number of samples that require drying and weighing makes direct measurement of forage biomass cost-prohibitive for a national feed inventory programme. Estimation techniques are employed to reduce the number of clipped samples and to reduce the amount of time needed to sample each location. Two popular methods that have been developed for estimation of forage biomass in rangeland vegetation include the weight unit method and the double sampling method.

For the weight unit method (USDA, 2003), a weight unit is established for each of the plant species occurring in the area of interest. The weight unit can be a whole plant, a plant part or a group of plants, and the size and the weight will vary with the size of the plant (e.g. grasses and forbs can be of smaller size and weight than a weight unit for a shrub species). Once the weight units are established, field personnel calibrate their estimation by visually selecting a plant or plant part that has weight equivalent to the weight unit. The plant biomass is then harvested, weighed and compared with the weight of the weight unit. This process is repeated until personnel can accurately estimate the weight unit. Once

Photo 16.3
A quadrat clipped at a placement along a line transect

NOTE: AN EXTENDED FIBERGLASS TAPE MEASURE, AS DEPICTED HERE, CAN BE USED AS THE REFERENCE FOR THE TRANSECT LINE IN GRASSLAND VEGETATION the calibration is completed, quadrat sampling is conducted in which the number of weight units of each plant species within the quadrats are estimated and recorded. The quadrat is then clipped by species to compare the harvested species weights against the weight units. This process is repeated until a reasonable level of accuracy is obtained between the weight unit estimation and clipped biomass for the quadrat. Once obtained, the biomass weight in the quadrats is estimated with weight units only. Quadrats can be clipped periodically to ensure that accuracy is being maintained. The harvested plant biomass is kept and later oven dried and weighed to calculate a dry matter conversion factor. The weight unit method can allow rapid sampling of a site once the estimations by personnel are calibrated and it reduces the number of samples that need to be clipped and subsequently weighed, thus reducing overall time and effort for sampling. A detailed description of this method can be found in the United States Department of Agriculture National Range and Pasture Handbook (USDA, 2003).

Double sampling methods generally involve development of a statistical relationship between biomass and visual estimates or an easily measured variable such as plant cover, height or age (Catchpole and Wheeler, 1992). To develop the statistical relationship, the visual estimate or measurement of the easily measured variable is collected at a number of sample points where biomass is clipped and weighed. A regression equation can then be developed between the easily measured variable and the biomass weights. Intensive sampling can then be conducted for the easily measured variable and the regression equation used to convert the measurements to biomass, thus reducing the need for additional clipping of vegetation. In developing the regression equations, initial sampling should be done to capture the range of both vegetation biomass and the easily measured variable.

A large number of double sampling techniques have been developed for estimation of forage biomass on rangelands. Catchpole and Wheeler (1992) provide an excellent overview of such techniques that use easily measured variables combined with a discussion of the advantages and disadvantages of each technique with regard to cost, accuracy, vegetation structure and variability. Herrick *et al.* (2005) provide an overview of double sampling using visual estimation for use in arid and semi-arid grassland, shrubland and savanna ecosystems.

16.2.5 Landscape stratification and scaling up

In developing a programme for quantifying rangeland forage biomass for a national feed inventory programme that uses direct measurement or biomass estimation techniques, it is necessary to develop a sampling framework that encompasses the range of plant communities and vegetation types that are grazed by livestock. It is also necessary to optimize the number of sample locations to reduce costs and ease logistical constraints. From the local to national level, a stratification scheme needs to be developed to ensure that sampling is representative of the vegetation types and productivity at each scale. The stratification needs to be designed where biomass results could easily be scaled up and aggregated to the regional and national levels in a spatially coherent manner. The use of spatial data layers such as digital elevation models (DEMs), soil and vegetation maps, and satellite images within GIS software assists in defining monitoring units having relatively uniform soils, vegetation and management characteristics (Herrick *et al.*, 2005). Logistical constraints such as road access, travel time and security are also factored into the GIS to delineate a manageable number of monitoring units to meet the goals of the national inventory. Field teams then conduct field sampling for forage quantity assessment in each of the monitoring units. Forage biomass (kg/ha) measured in each monitoring unit are then converted to total kilograms per monitoring unit through multiplication of the measured biomass and the area (ha) of the monitoring unit. A simple aggregation to the national level is then conducted by summing the forage biomass (kg) across all monitoring units in the nation, thus providing a national estimate of biomass (kg or tons) for the entire country. However, a more complex aggregation method probably needs to be employed to represent forage biomass for different kinds of livestock (e.g. cattle, sheep and goats). In addition, forage biomass amounts need adjustments for factors that reduce accessibility of livestock to graze forage biomass such as steep terrain, water availability and restricted access (e.g. national parks or conservation areas).

16.2.6 Forage quality assessments

Forage quality can be defined as the "degree to which a forage meets the nutritional requirements of a specific kind and class of animal" (Allen and Segarra, 2001). The assessment of forage quality for livestock management is important because forage quality is a primary driver for maintaining animal condition, reproductive health and livestock productivity which, in turn, influences economic return (Fales and Fritz, 2007). Moreover, the quality of the forage influences palatability, and therefore intake of forage by the grazing animal. Although forage quantities may be high, the vegetation may not be grazed due to the low quality of the available forage, thus reducing animal productivity and increasing use in areas with higher quality forage.

Because of the large land areas that rangelands/grasslands occupy, the diversity of the vegetation and grazing animals, movement of animals across the landscape and the variety of livestock management practices used by producers, assessment of forage quality in rangeland and grassland situations can be challenging. Like assessments for forage quantity, different direct and indirect methods have been developed to assist in assessing forage quality. A basic overview of these methods and their potential for use in a national feed inventory programme is provided below.

16.2.7 Direct methods

Because grazing animals are selective in their choice of which plants to eat, one cannot simply analyse the plant biomass that is on offer and expect to obtain meaningful results of forage quality. Direct methods to assess forage quality generally involve observing animals while they are grazing and attempting to recreate the diet they have eaten, or to use esophageal or rumen fistulated animals where the forage eaten can be recovered and examined for quality. Observation methods include hand plucking (Devries, 1995; Kiesling *et al.*, 1969; Langlands, 1974) and bite counts (Glasser *et al.*, 2008; Ortega *et al.*, 1997; Timmons *et al.*, 2010).

Hand plucking involves following and observing the animals as they graze and then hand plucking similar plant parts from where the animals had grazed. The hand plucked samples can then be analysed for forage quality indicators such as crude protein, digestible organic matter, fiber, macronutrients and ash. Bite count methods involve following the animals and recording the number of bites the animal takes from specific plant species and plant parts (e.g. leaf, stem or flower) and recording the size of the bite. The recording is usually done into a voice recorder and transcribed immediately after the observation session (Glasser *et al.*, 2008; Timmons *et al.*, 2010). After each observation session, samples are collected from plants similar to those eaten by the grazing animal. The samples are either clipped or hand plucked and the amounted sampled is in proportion to the bite sizes recorded and the observed plant parts eaten by the grazer. The samples are then analysed for forage quality indicators.

Both the hand plucking and bite count methods have limitations for application in a national feed inventory. For example, both methods are very time-consuming and require the use of relatively tame animals in order to be able to observe the grazing behaviour (Gordon, 1995). In addition, observers must be well trained in the methods to ensure that plants and plant parts are identified properly and that bite size designations are consistent among observers.

The use of esophageal or rumen fistulated animals is generally accepted as one of the more accurate methods for obtaining a representative sample of what the animal has eaten (Pfister *et al.*, 1990; Holecheck *et al.*, 1982). These animals are surgically altered to insert an opening (fistula) in either the esophagus or rumen. The opening is allowed to heal and kept closed with rubber or plastic plugs until needed for sampling.

For forage quality sampling with an esophageal fistulated animal, the animal is prepared for sampling by removing the plug and placing a bag over the esophageal opening. The animal is then allowed to graze, and the plant material which is eaten (extrusa) falls out of the esophageal opening and into the bag. At the end of the grazing session, the bag is removed and the fistula is plugged. The extrusa is removed from the bag, oven or freeze dried, and then analysed for forage quality indicators such as crude protein, fiber, digestibility and other nutrients.

For a rumen fistulated animal, the animal is prepared for sampling by removing the rumen plug/cover and conducting a total evacuation of the rumen contents (Ganskopp and Bohnert, 2006; Hirschfeld *et al.*, 1996). The interior of the rumen is cleaned with water to remove all remaining material. The plug is replaced and the animal is allowed to graze for a session of 60 to 90 minutes. After the grazing session, the entire contents of the rumen are removed and later analysed for forage quality indicators.

The advantages of rumen fistulation over esophageal fistulation are that rumen fistulated animals tend to heal quicker after surgery and require less supervision and care during the grazing session (Holecheck *et al.*, 1982). Several disadvantages of using fistulated animals for forage quality assessment include the need to maintain a special herd of animals that require constant maintenance because of fistulation and the need to have highly trained personnel available to work with these animals (Van Soest, 1994). Because of these issues and the need to sample a large geographic space, the use of fistulated animals to assess diet quality for a national feed inventory is most likely not practical.

16.2.8 Indirect methods

Indirect methods of determining forage quality generally involve examinations of the livestock faeces for indicators that can be correlated with the quality of the forage eaten by the grazing animal. Early work on indirect methods involved examination of the constituents of faeces such as faecal nitrogen (Holechek *et al.*, 1982; Squires and Siebert, 1983) and fiber components. For example, Wofford *et al.* (1985) used faecal nitrogen, non-fiber bound nitrogen, neutral detergent fiber, acid detergent fiber, acid detergent lignin and acid/pepsin disappearance as independent variables in regressions to predict forage intake, diet *in vivo* digestibility and diet nitrogen. Results indicated that faecal nitrogen did relatively well in predicting diet nitrogen which is useful in detecting crude protein deficiencies in cattle. However, predictive capability of intake and digestibility using faecal constituents was low.

Over the past 20 years, Near Infrared Reflectance Spectroscopy (NIRS) scanning of livestock faeces has emerged as a reliable tool for assessing the quality of forage grazed by ruminants (Dixon and Coates, 2010; Leite and Stuth, 1995; Li *et al.*, 2007; Lyons and Stuth, 1992; Showers *et al.*, 2006; White *et al.*, 2010; Dixon and Coates, 2009). The methodology for developing faecal NIRS (FNIRS) scanning capabilities involves development of reference equations that statistically compare near infrared spectral characteristics of the livestock faeces with quality constituents (e.g. crude protein, digestibility, fiber) of the forage eaten by livestock. Pairs of livestock diets and faeces that are needed for equation development can be gathered from feeding trials using penned animals (e.g. Li *et al.*, 2007; Showers *et al.*, 2006) or from trials using fistulated animals and free-ranging livestock (e.g. Leite and Stuth, 1995; Lyons and Stuth, 1992).

For pen feeding trials, forages are gathered by hand and mixed to create a known diet. A range of qualities and mixes of plant species are used to capture the variety in the local area or region. The diets are then fed to livestock and faeces are collected from the animals for a period of days after feeding. For trials using fistulated animals, the animals are grazed in pastures having free-ranging livestock and the extrusa collected is used to represent the diet of the livestock. Faecal samples are collected from the free-ranging animals for a period of days after extrusa collection.

For both of the above methods, the diets are analysed for quality constituents and the faecal samples are scanned with the NIRS instrument. NIRS software is then used to develop a multivariate equation that predicts the quality of the diet from the spectral characteristics of the faeces. Statistics such as standard errors and regression r^2 values can be calculated to assess the robustness of the equations. NIRS scanning of faeces for forage quality constituents generally has an accuracy that is similar to that of standard laboratory methods (Dixon and Coates, 2010; Lyons and Stuth, 1992; Showers *et al.*, 2006; Decruyenaere *et al.*, 2009).

The advantages of FNIRS are that it provides a rapid and reliable means of assessing the quality of forage the livestock animal is eating (Dixon and Coates, 2009), samples can be easily acquired without destructive harvesting, and the forage quality information provided can assist livestock producers in managing the nutritional needs of their herds to meet production goals (Dixon and Coates, 2009; Dixon and Coates, 2010). Disadvantages of FNIRS include the high up-front cost of the NIRS equipment, the need to develop feeding trials and equations that encompass the range of forage types and qualities that are encountered by the grazing animals in the region, and the need for independent validation of the FNIRS equations (Decruyenaere *et al.*, 2009).

For a national feed inventory, FNIRS may be the most practical choice to assess diet quality across a nation. A research centre or project can be assigned to develop equations using livestock research herds and feeding trials to develop the equations needed for forage quality evaluation. However, the costs of equipment, training of personnel and logistics of gathering a large number of faecal samples to represent a region may be prohibitive.

16.3 REMOTE-SENSING APPROACHES FOR FORAGE QUANTITY AND QUALITY ASSESSMENT

The use of remote-sensing imagery is attractive for assessing vegetation conditions on rangelands because of the large areal coverage it provides, the ability to examine remote areas that may be inaccessible and the ability to receive information at greater temporal frequencies than from field sampling. Since the 1970s, remote-sensing imagery has been used to assess vegetation conditions on rangelands. For example, Rouse *et al.*(1973) used multispectral scanner (MSS) imagery to examine green-up and developed a vegetation index that was correlated to vegetation biomass. Since that time, many different approaches have been used to examine conditions on rangelands and for quantifying biomass.

Vegetation indices derived from remote-sensing images are one of the more popular and extensively studied products for assessing vegetation biomass. Vegetation indices are transformations of spectral bands of the electromagnetic spectrum, measured as reflectance from the earth's surface by earth-observing satellites. These indices permit examination of the spatial and temporal variation and relative contribution of vegetation properties such photosynthetic activity and canopy structure (Huete *et al.*, 2002). Vegetation indices can provide an unbiased representation of vegetation without regard to the soil type, land cover classification or climatic condition (Huete *et al.*, 2002). Since the early 1970s, a variety of vegetation indices have been proposed (see Tucker, 1979; Huete *et al.*, 2002 for a review of indices). These generally involve some combination of the red and near infrared (NIR) portions of the electromagnetic spectrum, specifically wavelengths in the 0.6–0.7µm (red) and 0.75–1.1 µm (NIR) ranges (Tucker *et al.*, 1983). In the red range, much of the incident radiation is absorbed by leaf chlorophyll, whereas in the NIR range, the incident radiation is reflected by the leaf mesophyll cells. This provides a sharp contrast in the light reflectance back to the satellite that can be used for deriving ratios or indexing (Gitelson, 2004; Hurcom and Harrison, 1998; Brown *et al.*, 2006).

Of the various vegetation indices, the Normalized Difference Vegetation Index (NDVI) is the most used and accepted historically (Cracknell, 2001). It was first proposed as the "Band Ratio Parameter" by Rouse *et al.* (1973). It came into wider use with the launch of the NOAA's Advanced Very High Resolution Radiometer (AVHRR) instrument that had non-overlapping red and NIR spectral bands, thus allowing calculation of vegetation indices (Tucker *et al.*, 2005). NDVI is computed from the red and NIR bands as follows:

$$NDVI = (\rho_{nir} - \rho_r) / (\rho_{nir} + \rho_r)$$

where ρ_{nir} and ρ_r are the spectral reflectances of the near-infrared and red wavelengths, respectively.

The index has a range of -1 to +1. Increasing amounts of vegetation move the index toward 1. Bare soil and rocks have similar red and NIR reflectances so the index is near zero for these surfaces. Snow, water, and clouds have higher red reflectance than NIR reflectance, so NDVI values for these surfaces are negative (Hurcom and Harrison, 1998). NDVI has been used as a surrogate to estimate leaf area index, vegetation biomass and fraction of absorbed photosynthetically active radiation (FAPAR) (Asrar *et al.*, 1984; Sellers, 1985; Tucker, 1979).

Currently, multiple satellite platforms exist that are producing remote-sensing imagery and many of the products are freely available. The increased availability and generally low cost have made remote-sensing imagery an attractive tool for monitoring landscape conditions. The low cost and dense dataset that it provides make it an appealing product for use in a national feed inventory. Below is an overview of remote-sensing applications for forage quantity and quality assessments with a discussion of empirical and remote-sensing input model approaches.

16.3.1 Forage quantity

Two approaches have generally been used for assessment of biomass using remote-sensing imagery. These are: 1) empirical models that predict the forage biomass based on a statistical relationship between the spectral bands (or some combination of bands) in the image and vegetation biomass, and 2) process models that use remote-sensing data as inputs for predicting vegetation biomass.

16.3.2 Empirical approaches

Empirical approaches for assessing biomass using remote-sensing products generally involve using a regression relationship between the remote-sensing product variable and field-collected data on biomass (Dungan, 1998). For example, Tucker *et al.* (1983) used both a linear and logarithmic regression between the NDVI and ground collected biomass data to predict biomass on a regional scale in the Sahel region of Senegal. In the Xilingol Steppe of Inner Mongolia, Kawamura *et al.* (2005) found that the Enhanced Vegetation Index (EVI) derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite was useful in predicting live biomass and total biomass. In New Zealand, forage in dairy pastures was predicted within a 10 percent error using a regression model that related NDVI and time of year to forage biomass (Mata *et al.*, 2007). For rangelands in Jordan, Al-Bakri and Taylor (2003) used a linear regression model to predict shrub biomass production. They stated that this approach has the potential for estimating carrying capacity for rangelands in Jordan. In Mongolia, rangeland biomass was estimated using a relationship between a vegetation health index and field-collected biomass data (Kogan *et al.*, 2004). The vegetation health index was calculated using NDVI and brightness temperatures from the AVHRR satellite. The index provides an indication of anomalous vegetation conditions. In the northern Great Plains of the United States, Frank and Karn (2003) found a non linear response between biomass and NDVI, but this relationship was highly correlated (r^2=0.83). In an examination of real-time mapping of biomass for fire risk assessment at Etosha National Park in Namibia, Sannier *et al.* (2002) used rapid field measurement techniques for grass and shrub vegetation and developed regression relationships between these and NDVI. They found good correlations between green biomass and NDVI, although the strength of these relationships was related to vegetation type. They concluded that the ability to predict biomass via these methods allows near real-time mapping of fire risk to be feasible for Etosha National Park.

16.3.3 Remote-sensing input models

One problem that has been noted for empirical models that use remote sensing data to predict biomass amounts is that they violate the regression assumption of no autocorrelation in the predictor variable(s) (Dungan, 1998; Foody, 2003). Given that most remote-sensing data is inherently autocorrelated (similarity in pixels as a function of distance), this assumption should not be ignored. One way of overcoming this is to use plant growth models that are driven by remotely-sensed input variables on a pixel-by-pixel basis. Reeves *et al.* (2001) describe such an approach for predicting rangeland biomass using remote-sensing products from the MODIS system and a light use efficiency model for plant growth. Their approach uses the MODIS imagery to estimate FAPAR, which is then fed into a light use efficiency model (Montieth, 1972, 1977) that estimates aboveground net primary productivity (ANPP). Regional maps of biomass are then produced at 1 km^2 resolution. Hunt and Miyake (2006) used a similar light use efficiency model to predict stocking rates within 1 km^2 cells for the entire state of Wyoming in the United States. Their model differed from Reeves *et al.* (2001) in that they used the NOAA Advanced Very High Resolution Radiometer (AVHRR) to estimate FAPAR and they converted aboveground net primary production to available forage to remove biomass not usable by livestock.

Although much evidence exists that the application of biomass prediction on rangelands using remote-sensing variables is feasible, the extrapolation of these relationships to new areas is not always feasible or recommended. Generally, field data need to be collected for new areas or regions to develop the prediction equations. Another issue is that many of these models predict vegetation biomass, but do not address forage availability to specific grazers. If forage deficits or surpluses for specific kinds of livestock are to be addressed in a national feed inventory, grazer specific equations or models need to be developed to address available forage. In a study examining the use of remote-sensing data for estimating forage biomass for carrying capacity assessments in Namibia, Espach *et al.* (2009) addressed issues of quantifying available forage by developing corrections for shrub biomass that was unpalatable or not available to grazers.

16.3.4 Forage quality

Research on using remote-sensing to estimate forage quality is not as extensive as that for the estimation of biomass. This is probably related to the difficulties involved in acquiring forage quality information to use in empirical and modelling approaches. Another issue is that as remote-sensing data becomes coarser in resolution, the pixel becomes an integrated representation of the vegetation, therefore making it more difficult to separate out the vegetation components that are eaten by the grazing animal. It also makes it difficult to determine an appropriate sampling scheme to measure forage quality, especially when vegetation becomes more heterogeneous and when multiple grazing animals are using the area.

16.3.5 Empirical approaches

Empirical approaches for estimating forage quality generally involve examining statistical relationships between forage quality variables and spectral information from remote-sensing imagery. Thoma *et al.* (2002) used simple linear regression with NDVI as the independent variable to predict forage quality and quantity on rangelands in Montana, United

States. They reported reasonable relationships between NDVI and live biomass (r^2 = 0.68), total biomass (r^2 = 0.68), and nitrogen in standing biomass (r^2 = 0.66), but found poor relationships with biomass (r^2 = 0.18) and nitrogen concentration (r^2 = 0.01) in standing dead biomass. In China, regression equations using the Enhanced Vegetation Index (EVI) derived from the MODIS sensor were used to predict live and dead biomass and crude protein in standing biomass (Kawamura *et al.*, 2005). They found good predictability between standing live biomass and total biomass (green + dead) (r^2 = 0.77 to 0.80), but found poor correlations with crude protein (r^2 = 0.11).

Using faecal NIRS techniques to determine diet quality for white tail deer in Texas, United States, Showers *et al.* (2006) examined the ability of NDVI to predict deer diet quality. They found strong statistical relationships between NDVI and diet quality variables (crude protein, digestible organic matter and phosphorus) for all seasons (r^2 >0.70), with the exception of phosphorus in the winter.

16.3.6 Geostatistical interpolation

For a national feed inventory programme, the ability to map forage quality for a region or entire country is very useful. Because of the logistics and costs, it is likely be impractical to collect enough data to map forage quality based only on data collected from the field using direct or indirect methods. However, interpolation techniques such as co-kriging can be useful in mapping expensive, hard-to-collect variables given the availability of a second correlated variable that is easier and less costly to collect. Co-kriging is a geostatistical interpolation technique that calculates estimates for unknown points by using the weighted linear average of the available samples of the primary and secondary variables. The secondary variable (covariate) is cross-correlated with the primary variable of interest and is usually sampled more frequently and regularly (Isaaks and Srivastava, 1989), thus allowing estimation of unknown points using both variables. Remote-sensing imagery provides a dense and exhaustive data set that can serve as a secondary variable for geostatistical interpolation, given that a correlation (both direct and spatially) exists between the primary and secondary variable (Dungan, 1998). Co-kriging of forage quality was tested for cattle in Ghana using FNIRS-estimated diet quality attributes as the primary variable and NDVI as the secondary variable (Awuma *et al.*, 2007). Diet quality attributes (crude protein and digestible organic matter) were collected from cattle at selected households throughout Ghana during 2000. The diet quality variables were paired with NDVI extracted for the pixels at the location and date of the faecal collection. The diet quality and NDVI data were subject to co-kriging analysis and maps were produced for the diet quality variables. Validation results indicated that co-kriging did a reasonable job of predicting crude protein during the dry season (r^2 = 0.687) but not quite as well in the wet season (r^2 = 0.513). For digestible organic matter, the co-kriging prediction was poor for the dry season (r^2 = 0.13), but did reasonably better for the wet season (r^2 = 0.548). It was speculated that this was related to the amount of shrub cover in some of the sampling areas that did not contribute to the available forage for cattle, but increased the greenness signal in the NDVI. The results of this study do indicate that the technique of mapping forage quality is feasible but additional study and validation will be needed to improve the results for use in national programmes.

16.4 USE OF SIMULATION MODELS FOR ESTIMATING FORAGE QUANTITY

Simulation modelling offers unique capabilities for estimating forage quantity for a national feed inventory programme. Although the initial efforts required to parameterize, calibrate and validate a simulation model can be time-consuming and expensive, especially for a national effort, the capabilities that simulation modelling provides, such as near real-time monitoring, forecasting and exploration of alternatives, make it an attractive choice for a national feed inventory programme. The use of simulation models for rangeland and grassland analysis has increased in the past 30 years due to increased computing capacity, accessibility of programming languages and availability of data to parameterize the models. Rangeland/grassland simulation models have differing levels of complexity and many are designed to not only simulate biomass production but also examine other aspects such as hydrology, erosion, livestock production, ecosystem services and/or economics in an integrated, interacting framework. This framework allows users to examine ecosystem processes and management alternatives, and to predict response to differing alternatives (Wight and Skiles, 1987; Bouraoui and Wolfe, 1990; Carlson and Thurow, 1992). An overview of models that have been used for predicting biomass on rangelands is provided below along with examples of using simulation modelling in an integrated framework for risk management and decision-making.

16.4.1 Rangeland models

One of the first comprehensive rangeland simulation models was Simulation of Production and Utilization of Rangelands (SPUR) (Wight and Skiles, 1987). SPUR simulates rangeland ecosystem function and allows evaluation of changing management practices. The model is physically-based and has integrated climate, hydrology, plant, animal and economic modules (Carlson and Thurow, 1992; Hanson *et al.*, 1992; Foy *et al.*, 1999; Pierson *et al.*, 2001). The SPUR model has been exercised in several different geographic locations to ascertain its ability to predict biomass production. For example, in a field study in north-central Texas, United States, Teague and Foy (2002) found a good agreement between the model output and measured aboveground biomass for warm season grasses and poor agreement with total aboveground biomass for cool season grasses. In southwestern Idaho, United States, SPUR model output was compared with peak standing biomass for shrubs (sagebrush), grasses and miscellaneous forbs (Pierson *et al.*, 2001). Bottlebrush squirreltail grass (*Elymus elymoides*) biomass had the best correspondence with model output during the eight year time period examined, whereas sagebrush (*Artemisia tridentata* ssp. *wyomingensis*) and Sandberg bluegrass (*Poa sandbergii)* biomass corresponded to the model in four out of eight years and three out of eight years, respectively.

Other simulation models capable of predicting rangeland biomass include the Water Erosion Prediction Project (WEPP) (Flanagan and Nearing 1995), the Agricultural Land Management Alternatives with Numerical Assessment Criteria (ALMANAC) (Kiniry *et al.*, 2002), and the Ecological Dynamics Simulation Model (EDYS) (Childress *et al.*, 2002). The WEPP model was primarily developed as a replacement to the Universal Soil Loss Equation (USLE) with its primary focus on water erosion and sediment loss, but forage growth and grazing can be simulated to complement the erosion information (Flanagan and Nearing, 1995). The ALMANAC model is a multi-species model that predicts biomass and also simulates water and nutrient balance (Kiniry *et al.*, 2002). It was developed to perform across a wide variety of soils and climatic conditions and is currently being used as the simulation model for rangeland biomass assessment for the Rangeland Conservation Effects Assessment Program for the United States Department of Agriculture. The EDYS model is a general rangeland process model capable of modelling changes in biomass as well as relevant ecological processes such as physical disturbance, plant uptake and growth, fire, herbivory, and management activities (Childress *et al.*, 2002). It can model these dynamics at the plot scale, but can also be run in a gridded environment to capture spatial variability and to allow scaling. The model has been used to examine impacts of military training on vegetation and soil erosion, the impacts of expanding wild elk herds on winter pasture and endangered species habitat, and impacts of woody plant invasions.

Another comprehensive rangeland biophysical model is the Phytomass Growth Simulator Model (PHYGROW) (Stuth *et al.*, 2003b). PHYGROW is a multi-species plant growth model capable of simulating biomass production, soil water dynamics, runoff, selective grazing by livestock and stocking rates of multiple livestock species. The plant growth sub-model in PHYGROW is a light use efficiency model (Montieth, 1972 1977) that simulates plant growth optimal conditions (water non-limiting). The model then discounts plant growth based on the amount of water stress, temperature stress and livestock grazing demand based on the input climate variables and grazer herd composition and plant preferences. The grazing and stocking rate sub-model allows biomass to be selectively grazed by multiple kinds/classes of livestock having differing forage demands and forage preferences (Stuth *et al.*, 2003b; Quirk and Stuth, 1995), thus allowing accounting of available forage by grazer. The model is the foundation of the regional livestock early warning system (LEWS) in East Africa (Ryan, 2005; Stuth *et al.*, 2003a; Stuth *et al.*, 2005) and Mongolia (Angerer, 2008; Bolor-Erdene *et al.*, 2008). LEWS was developed for assessing near-real time forage conditions for managing drought and livestock movement.

The Agriculture Policy/Environmental Extender Model (APEX) (Williams *et al.*, 2008) has been used in a variety of pasture systems in the United States and elsewhere for conservation effect assessments and examination of best management practices. One of the unique aspects of APEX is that the model provides the ability to simulate management on whole farms, pasture systems or small watersheds in order to examine practices in relation to ecosystem services (e.g. water quality, soil quality, carbon sequestration, etc.). The model also allows evaluation of various management practices such as terracing, grass waterways, buffer strips, crop/pasture rotations, irrigation, drainage systems and manure management. The model is currently being updated to improve the grazing algorithm for simulating selective grazing in order to extend the capabilities of the model for rangelands (J. Williams, personal communication).

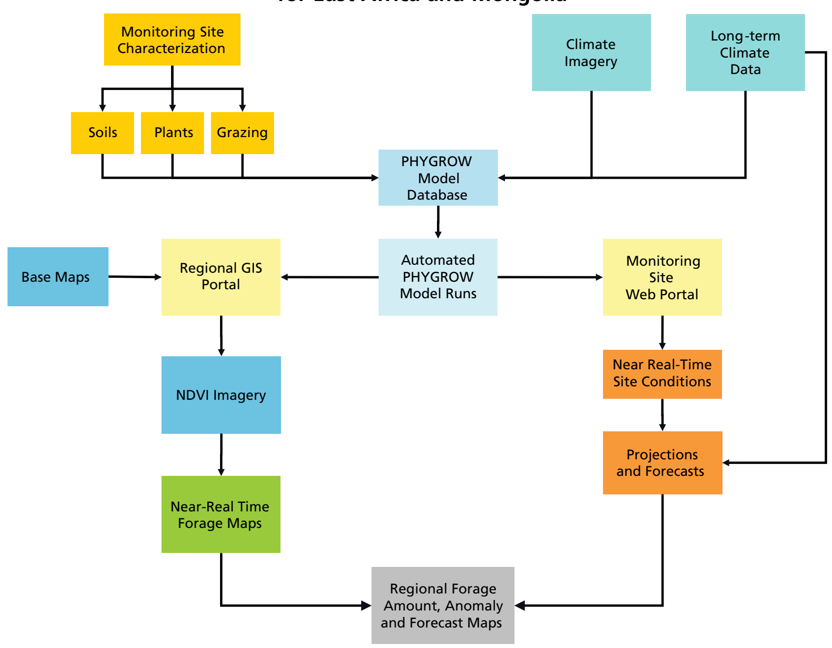
16.4.2 Integrated approaches

Field-collected data, simulation model output and remote-sensing data can be integrated into a GIS to produce comprehensive outputs that can enhance the products produced for a national feed inventory programme. In addition, an integrated GIS framework can allow the use of geostatistical tools that can provide capabilities for interpolating forage quantity and quality point data or improve interpolation by taking advantage of cross-correlations between the forage data and remote-sensing variables.

An example of an integrated approach to forage quantity assessment on a regional level is the Livestock Early Warning System (LEWS) in East Africa (Stuth *et al.*, 2003a; Stuth *et al.*, 2005) and Mongolia (Angerer, 2008; Bolor-Erdene *et al.*, 2008). LEWS was developed to provide near real-time estimates of forage biomass and deviation from average conditions (anomalies) to provide pastoralists, policy-makers and other stakeholders with information on emerging forage conditions to improve risk management decision-making. The system combines field data collection from a series of monitoring sites, simulation model outputs, statistical forecasting and GIS to produce regional maps of current and forecast forage conditions (Figure 16.1). The system uses the PHYGROW simulation model as the primary tool for estimating forage conditions. Data on plants, soils, and grazers are collected from monitoring sites in the field and the data are stored in the PHYGROW model database. Climate data are acquired from national data sources and also stored in the database. The data are used to parameterize and calibrate the model. The simulation model runs for each monitoring site are every 15 days and the outputs are made available via the GIS web portal. To produce maps of forage conditions, the total forage available to livestock is output for each monitoring site and is merged with NDVI data for the region. Co-kriging interpolation is then conducted to create regional maps of available forage. Anomaly maps (deviation from long-term average) of forage conditions are also produced to provide regional and local stakeholders with the ability to compare current conditions with those in the past and to identify areas of drought or poor forage conditions.

The LEWS system also incorporates a statistical forecasting system that provides a projection of available forage conditions for 60 days into the future. Using GIS, the total

FIGURE 16.1
Integrated framework for the Livestock Early Warning System modelling system for East Africa and Mongolia



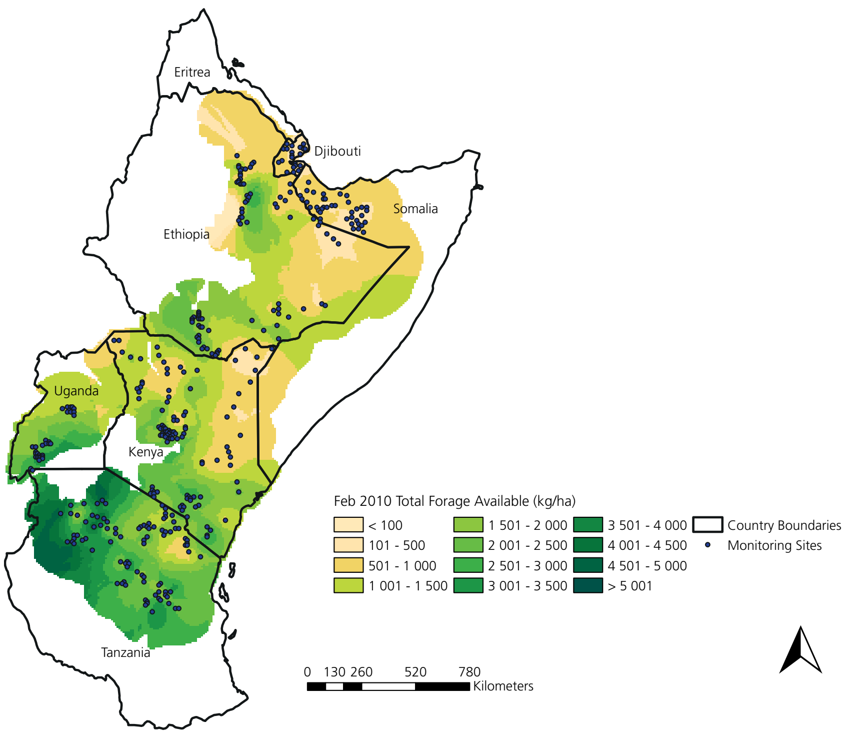
available forage (Figure 16.2) and forage anomaly maps (Figure 16.3) for East Africa are combined with base maps and are delivered to stakeholders.

To install a system like LEWS for a national feed inventory requires investment in field data collection at selected monitoring sites across the region. During the initial visits to the site, the field data collected are used to parameterize and calibrate the simulation model. Subsequent field visits to the monitoring sites are needed for further calibration and model validation to ensure that model outputs are accurate. In addition, investments in computer and database infrastructure are needed to accommodate the simulation modelling, data storage and GIS integration.

16.4.3 Ecosystem models

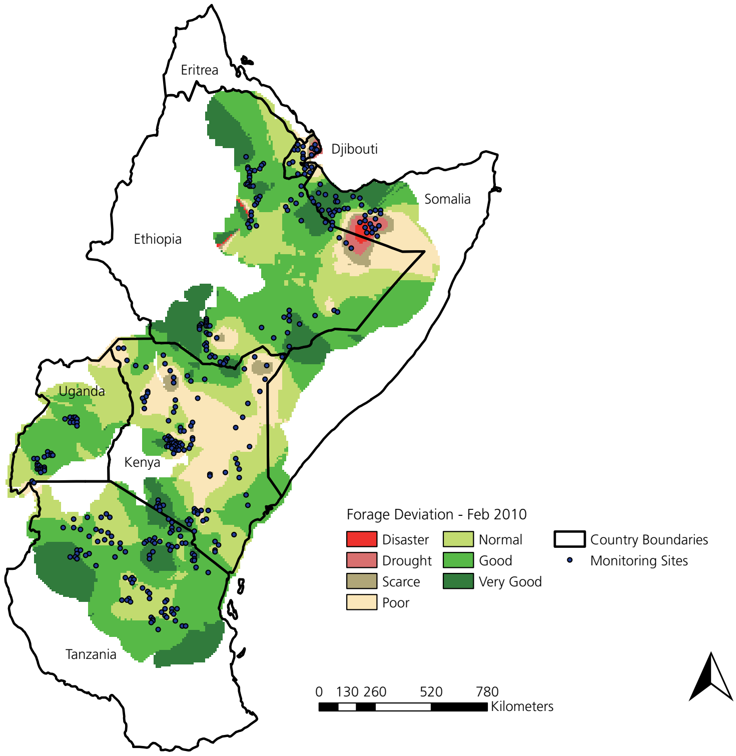
Ecosystem models provide an opportunity to examine, in an integrated fashion, the complex ecological and management processes that can influence forage biomass and quality changes over time. Instead of relying on empirical relationships for prediction, ecosystem models are process-based and are designed to simulate outcomes based on the complex

FIGURE 16.2
A map of total forage available to grazers in East Africa during February 2010 that resulted from co-kriging interpolation of PHYGROW model output and NDVI data



Note: These maps are made available to stakeholders for use in livestock management decision-making as part of LEWS in East Africa.

FIGURE 16.3
A map of forage deviation from long-term average (i.e. forage anomaly) in East Africa for February 2010



Note: Categories represent early warning indicators for management response. These maps are made available to stakeholders for use in livestock management decision making as part of LEWS in East Africa.

interactions among biotic, abiotic and human management processes. For a national feed inventory system, the use of ecosystem models provides the ability to holistically examine the processes of forage production and use by livestock and other herbivores. Specific causes for feed deficits or surpluses are also explored to assist in determining where mitigating measures are needed or where improvements can be made to the system.

The SAVANNA model (Coughenour, 1993; Chapter 15 of this Manual) is an ecosystem model that has been used extensively on rangelands in East Africa, Asia and the United States (Thornton *et al.*, 2006, Wiesberg *et al.,* 2006). It is a process-based, spatially explicit model that can simulate changes in forage quantity and quality in relation to climate, landscape position, plant community, selective herbivory and land management. The model is integrated with GIS to allow remote-sensing and spatial data layers to be easily incorporated into the model framework. The model contains modules for site hydrology, plant population dynamics, plant biomass production, herbivory, herbivore energy balance and grazing herbivore population dynamics. It is unique in its ability to simulate grazing animal movement in response to changing forage quantity and quality conditions, water distributions and topography, in addition to changes in population structure and herd productivity due to changes in vegetation quantity and quality (Ellis and Coughenour, 1998).

The SAVANNA model was originally developed to examine the ecosystem dynamics and coping strategies of pastoralists in the Turkana region of Kenya and has since been adapted to many other regions and grazing systems (Boone and Wang, 2007; Ellis and Coughenour, 1998). It has been used to assess forage-limited large herbivore dynamics in a wide variety of ecosystems worldwide (Coughenour 1999, 2002, 2005; www.nrel.colostate.edu/projects/savanna). Equal attention is given to animal and vegetation responses in terms of forage intake, energy balance, spatial distribution and population dynamics. A comparison of this modelling approach with others is provided by Weisberg *et al*. (2006). Christensen *et al.* (2003) used the model to examine productivity differences and livestock grazing dynamics under a range of stocking rates to provide insights into the sustainability of grasslands in Inner Mongolia in face of increasing grazing pressure. They identified thresholds where increased grazing pressure leads to changes in vegetation composition from herbaceous to shrub-dominated communities. Boone and Wang (2007) used the SAVANNA model to assess population dynamics of cattle under varying climatic regimes in Africa and found that precipitation amounts and variability were not always linked to changes in cattle populations over time. Plumb *et al.* (2009) used the model to examine carrying capacities for bison in Yellowstone National Park, United States, and were able to recommend a general number of bison that could be supported by the park over time.

In using an ecosystem model such as SAVANNA for a national feed inventory programme on rangelands, a significant amount of time and effort needs to be spent on acquiring the GIS data layers and collecting plant and animal data to parameterize the model. However, once the model is parameterized and calibrated, not only can estimates of forage biomass and quality be examined and mapped, but a whole range of other outputs can also be provided to assist decision-makers in understanding the underlying causes of feed deficits/surpluses.

16.5 INFLUENCES OF TERRAIN, WATER DISTRIBUTION AND OTHER FACTORS ON FORAGE AVAILABILITY

In previous sections, the concept of available forage was presented and the need to define available forage as being specific to the grazer(s) of interest was discussed. Other factors that can influence the availability of forage include terrain, distance to water and penetrability of shrubs and trees. The kind of grazing animal is also an important consideration because different kinds and classes of grazing animals differ in their ability to navigate these factors.

16.5.1 Terrain

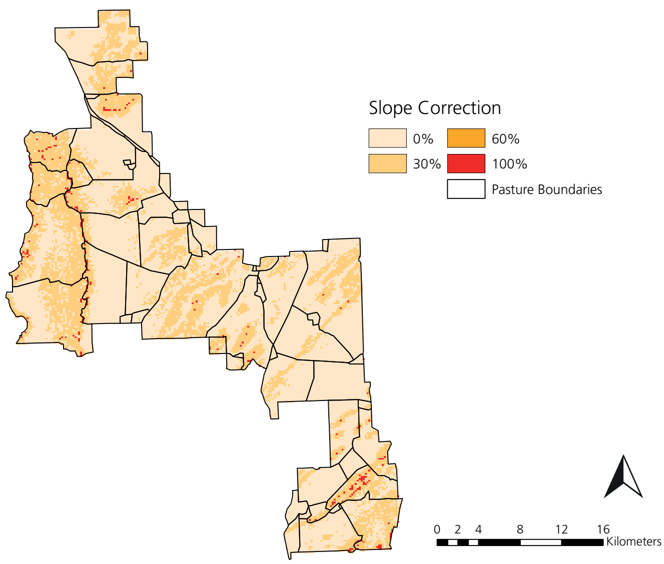
Features of the landscape terrain can influence how livestock utilize vegetation. Slope of the terrain can be a primary factor that influences the accessibility of forage to grazers. For cattle, steep slopes are hard to navigate; therefore, utilization of forage by cattle on slopes greater than 60 percent is generally very low. Holechek *et al.* (2001) provide guidelines to account for the reduced grazing capacity for cattle based on percentage of slope. For slopes of 0 to 10 percent, no reduction in grazing capacity is needed. For slopes of 11 to

30 percent and 31 to 60 percent, a 30 percent and 60 percent reduction in grazing capacity is recommended, respectively. For slopes exceeding 60 percent, these areas are considered inaccessible to cattle; therefore grazing capacity should be reduced by 100 percent. Sheep and goats, because of their smaller body and hoof size, can navigate and utilize vegetation on steeper slopes. In their guidelines for grazing capacity reductions for sheep, Holechek *et al.* (2001) recommend that slopes greater than 45 percent be considered unusable.

Determination of slope for grazing capacity reductions can be done using GIS software and Digital Elevation Model (DEM) data that are available to the public from various government sources. The resolution of the DEM datasets vary, so considerations need to be made as to the appropriate resolution of the data for the analysis. Higher resolution DEM data can capture more detail in slope variation across the landscape, but may increase analysis time and data storage requirements. Once the slope percentages are determined from the DEM, GIS software can be used to assign the appropriate reductions in grazing capacity (or forage availability) based on the steepness of the slope and the kind of grazing animal. Figure 16.4 depicts a GIS classification of slopes for grazing capacity reduction using the above protocol for cattle.

Another terrain factor that can influence utilization of forage on the landscape is the ruggedness or rock cover of the landscape. Cattle generally avoid very rocky surfaces, whereas sheep and goats can more easily navigate these. For example, Hohlt *et al.* (2009) found that cattle had preferences for grazing on specific soil types and areas where rock

FIGURE 16.4
Slope correction classifications for forage grazing capacity reductions based on steepness of slope



Note: The correction classifications indicate the percentage reduction in grazing capacity recommended for the slope class. For example, areas represented for the 30 percent slope correction have available forage amounts reduced by 30 percent for inventories or stocking rate calculations.

cover was below 30 percent. Assessing the degree of ruggedness and rock cover for terrain is difficult without field measurements or visual appraisals. High resolution aerial photography can provide information on these factors, but may not be practical for a national and regional programme due to cost and availability.

Spatial arrangement and density of vegetation, especially trees and shrubs, can influence use of forage on the landscape by grazing livestock. Thick, dense patches of shrubs and trees may be impenetrable for some kinds of livestock and therefore may impede foraging and reduce accessibility to forage beyond the boundary of the patch. On mixed-shrub/grass rangeland in the Edwards Plateau region of Texas, United States, Owens *et al.* (1991), found that as shrub abundance increased, utilization of the grasses by cattle decreased. They attributed this decrease to the physical barrier created by dense shrubs. In studies using GPS receivers on cattle, Hohlt *et al.* (2009) found that cattle in both the Edwards Plateau and southern regions of Texas, United States, avoided areas of thick, dense shrub cover. To assess density and impenetrability of shrubs so that forage availability reductions can be made, field data collection and classification of shrub/tree cover using remote-sensing imagery, or aerial photography can be used to map areas of shrub and tree cover. However, for a regional and national feed inventory programme, the costs and logistics for collecting this data may be prohibitive.

16.5.2 Distance to water

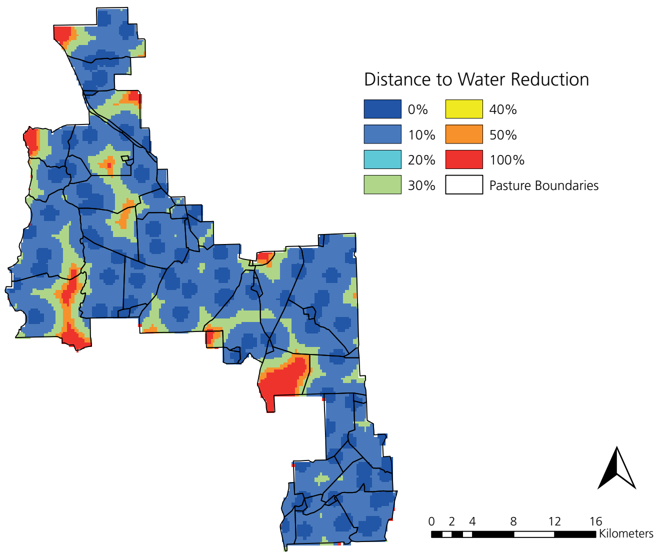
Another major factor influencing availability of livestock forage is distance to water. Like terrain, the degree to which this factor affects accessibility of forage is dependent on the kind of grazing animals. Cattle need water every day for efficient growth, therefore they generally will not utilize forage that is greater than 3.2 km from a water source (Holechek *et al.*, 2001). Sheep and goats can traverse greater distances for forage because they do not require water each day (McDaniel and Tiedeman, 1981). Desert cattle breeds also require less water. Camels, with their unique adaptations to go without water for long periods, are able to range extremely far from water.

Holechek *et al.* (2001) provide guidelines for reductions in cattle grazing capacity with increasing distance from water. For distances of 0 to 1.6 km, no reduction in grazing capacity is needed. For distances of 1.6 to 3.2 km, a 50 percent reduction is recommended. For distances greater than 3.2 km, a 100 percent reduction is recommended (ungrazeable).

Developing a map of grazing capacity reductions can easily be constructed using GIS software given that the locations of the water sources are known. Buffers of the distance classes can be built around each water point and merged to form a coverage of grazing capacity reductions. Figure 16.5 depicts a grazing capacity reduction map for water points within a pasture grazing system.

To incorporate grazing capacity reductions due to distance to water in a regional or national feed inventory programme, a comprehensive geodatabase of water locations needs to be developed. This database must be updated periodically to add new locations and provide status updates for those water points already included in the system.

FIGURE 16.5
Correction classifications for forage grazing capacity reductions based on distance to water



Note: The correction classifications indicate the percentage reduction in grazing capacity recommended for distance away from the watering point. For example, areas represented for the 50 percent distance to water correction have available forage amounts reduced by 50 percent for inventories or stocking rate calculations.

16.6 ASSESSING ANIMAL PRODUCTION RESPONSES TO FORAGE QUANTITY AND QUALITY

Because livestock production from grasslands and rangelands is a significant contribution to the overall GDP in many countries and is a component of the wealth and well-being of many people, especially pastoralists, the assessment of animal production as it is related to forage quantity and quality is important for monitoring at the national or regional level. Many countries conduct inventories of livestock, but rarely have the numbers of livestock been compared with the forage base to assess production capacity and/or sustainability of the forage resources. In the following sections, considerations for carrying capacity, stocking rate and nutritional balancing are discussed, as well as ways in which a national feed inventory programme can be used to gather information for sustainable livestock production and improved feed management.

16.6.1 Carrying capacity and stocking rate considerations

Once a national or regional inventory of forage biomass is conducted through direct measurements, remote-sensing methods, simulation modelling or combinations of these, then the forage biomass will need to be translated into numbers of animals that the forage base can support. Stocking rate can be defined as the number of animals allocated to a given land area for a specified time period. Grazing or carrying capacity can be defined as the maximum stocking rate for a given land area that can be used year after year without damaging the vegetation or other associated resources (e.g. soil, water quality, etc.) (Holechek *et al.*, 2001). Using the information on forage biomass, the characteristics of the grazing animal(s) and other data layers such as slope and distance to water, a stocking rate for the animals of interest can be calculated.

Calculation of stocking rate is conducted in four steps: 1) determination of available forage; 2) adjustments for slope and distance to water; 3) calculation of forage demand; and 4) calculation of stocking rate. For the first step, the amount of available forage for the animal(s) of interest can be assessed using the tools and methodologies described in the previous sections. As discussed above, the amount of forage that is available to a particular grazer on a landscape is dependent on the plant species present and the dietary preferences of the grazing animal. Therefore, the forage biomass estimates determined through the national feed inventory needs to be partitioned into available forage for each grazer so that stocking rates can be calculated. Because of dietary overlap among grazing animals, care needs to be taken in partitioning the forage biomass to each grazer so that the portion of biomass where the diets overlap is separated properly; otherwise, too many animals will be allocated to the given land area.

Once the available forage is determined, then the adjustments to available forage for slope and distance to water can be calculated. This can be done in a GIS where the available forage biomass data layer (Figure 16.6) is multiplied by the slope adjustment (Figure 16.4) and distance to water adjustment (Figure 16.5), resulting in a map of usable forage (Figure 16.7). The usable forage can then be aggregated up to a boundary (e.g. pasture, administrative boundary, etc.) resulting in the total kilograms of usable forage for the area of interest.

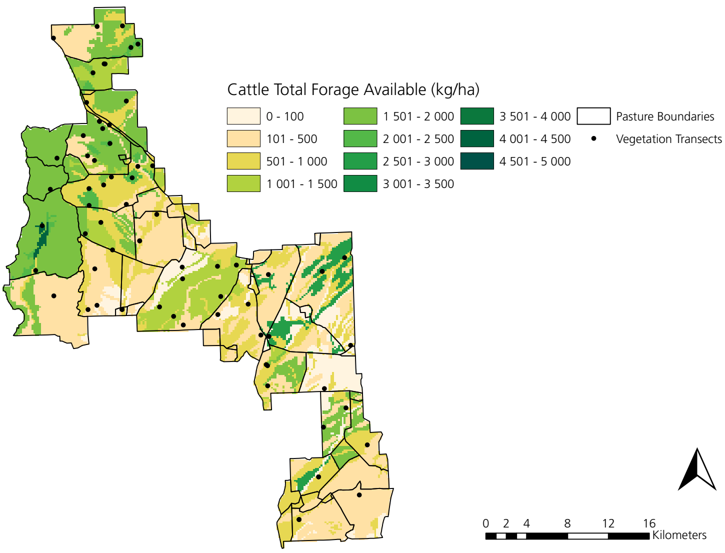
Once the usable forage is determined, then the forage demand for the grazer of interest needs to be determined. The dry matter intake of most ruminants is 2 percent of their body weight (Holechek *et al.*, 2001). Therefore, the average weight of the grazer can be multiplied by 2 percent to determine daily intake of forage. This is then multiplied by the number of days of grazing resulting in the forage demand per grazing animal for the grazing period (kg/head/period).

For the stocking rate calculation, the total usable forage (from step 2) needs to be partitioned into forage that should be sustainably utilized for grazing by the animal (i.e. percent allowable use) and forage residue that will be left on the site to protect the soil and regenerate the plants. The percent of allowable use varies by vegetation type and climate, generally by from 25 to 50 percent. Holechek *et al.* (2001) provide guidelines on allowable use values for different vegetation types and rainfall regimes. After the total usable forage is multiplied by the percent of allowable use, the product provides the total kilograms of forage that is available for grazing. This amount is then divided by the forage demand (step 3) resulting in the total number of animals that can graze the area of interest.

The steps for calculating stocking rate (adapted from Holechek *et al.,* 2001) are summarized below:

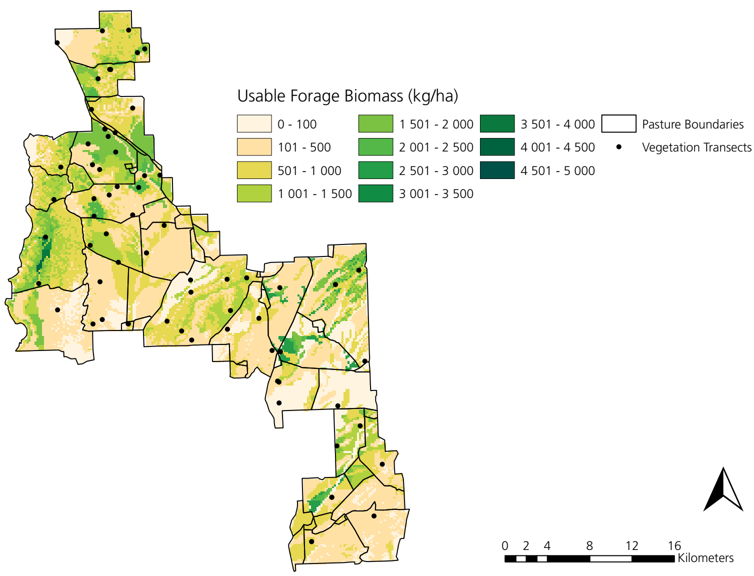
1. *Determination of available forage (kg/ha of dry matter) for a given land area*.
   Assessed through direct field measurement, remote-sensing methods, simulation modelling or combinations of these.

FIGURE 16.6
Total forage available (kg/ha) for cattle in a pasture grazing system



Note: Total forage was assessed using field collected data and simulation modelling (PHYGROW).

FIGURE 16.7
Total usuable forage for cattle after total forage available (Figure 16.6) was corrected for slope (Figure 16.4) and distance to water (Figure 16.5) grazing capacity reductions



2. *Calculation of usable forage (total kg dry matter) for area of interest*.

Available forage (kg/ha)	x slope correction
	x distance to water correction
	x area (ha)
	= total usable forage available for grazing (kg)

3. *Calculation of forage demand*.

Weight of grazer (kg)	x daily dry matter intake (2 percent of body weight)
	x length of time area will be grazed (days)
	= forage demand per grazer for grazing period (kg)

4. *Calculation of stocking rate*.

Total usable forage (kg)	x allowable use (percent)
	÷ forage demand per grazer (kg)
	= number of grazing animals (hd)

An important consideration in developing the stocking rates is to account for wildlife use of forage, and events that may reduce the amount of forage such as fire. In areas such as Africa where livestock and wildlife share grazing areas, accounting for forage use by wildlife is extremely important otherwise stocking rate calculations result in allocating more animals than an area can sustainably support. Also, for national inventories, it is important to have good base maps of national parks boundaries, reserves and other non-grazeable areas so that these land areas are not included in the forage inventory or stocking rate analysis.

16.6.2 Nutritional balancing

For forage quality assessments, nutritional balancing decision tools can be useful in assessing supplemental feed requirements for enhancing/maintaining production and optimal strategies for supplemental feeding during rangeland forage shortages. Nutritional balance software is available that allows users to input information on the quality of the forage the animals are grazing and receive information on what supplemental feed is needed for maintaining performance goals. One such software package is NUTBAL (http://cnrit.tamu.edu/), which models the crude protein and net energy status of cattle, sheep and goats. This computerized decision aide allows the user to enter the kind, class and breed of animal to be monitored, current body condition, current climate conditions, weight performance targets and forage quality information (crude protein and digestible organic matter). A nutritional balance is calculated and a report is provided describing the protein and net energy conditions for the animal. If a protein or energy deficiency exists, a least cost ration is calculated from a list of feeds or fodders available to the user.

Additional decision support tools for nutritional balancing include the Small Ruminant Nutrition System (http://nutritionmodels.tamu.edu/srns.htm) and the Langston University Nutrition Requirements for Goats calculator (http://www.luresext.edu/goats/research/nutreqgoats.html). Both have been designed to address nutritional balances for sheep and goat nutrition.

16.7 DATA MANAGEMENT FOR A NATIONAL FEED INVENTORY PROGRAMME

For a national feed inventory programme to be successfully implemented, data management and quality control infrastructure will be needed. The large amount of data that are generated as part of the inventory need to be stored in relational databases to ease data summary and availability. If remote sensing and/or simulation modelling are used, computing systems capable of handling and storing this type of data, as well as possessing the capability to run the software efficiently, will be required. Since much of the data will be spatial in nature, a GIS that is integrated with the inventory database will ease analysis, reporting and map production. Finally, qualified personnel will be needed to maintain, enhance and troubleshoot the system in order for the system to be sustainable. The data management, GIS and personnel requirements that need to be considered for implementing a national feed inventory are described below.

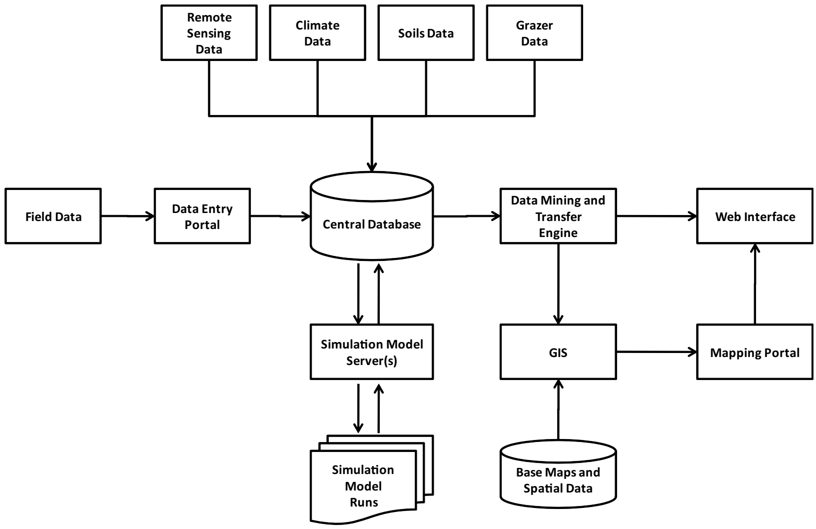
16.7.1 Data management and infrastructure

Regardless of methodology used to gather data on forage quantity and quality, a tremendous amount of data will need to be acquired and managed for a national feed inventory programme. Prior to implementation of the feed inventory, a data management plan will need to be developed that outlines how data will be collected, how and where it will be stored, and methods for data access. Once the data management plan is agreed on, the necessary infrastructure to support the data storage and analysis will need to be purchased and installed. Figure 16.8 provides a generalized structure of a data management system for a national feed inventory. The core of the system is a centralized database that stores data and allows easy retrieval. Field data are collected and entered into a data entry portal which ensures that all the required information is input into the central database in a standardized format. Remote-sensing, climate, soils and grazer information can be gathered from other sources and stored in the database. In the case of remote-sensing and climate data, these may be links to remote systems for near real-time data acquisition. If simulation modelling is used for the inventory, the centralized database can integrate the field data and data from other sources to provide inputs to the simulation model, and act as storage for the simulation model output. A data transfer and mining engine extracts data and transfers it to a web portal or a GIS. The web portal acts as the user interface for extracting reports or data from the feed inventory system. Linkages to the GIS allow mapping and spatial analysis of data that can be displayed via a mapping portal or integrated into the web portal.

Equipment needed for this data management system includes disk arrays for the centralized data storage and backup, web servers for the data entry and web portals, workstations or server(s) for the GIS, server(s) for simulation modelling, and backup power supplies. Infrastructure includes a secure space to house the equipment that has adequate power and cooling. A high-speed internet connection is needed for efficient data download and web presence.

To reduce software costs, open source software such as PostgreSQL (http://www.postgresql.org/) could be acquired for database management. For data entry, data transfer and mining engine, and web portal, software and web pages need to be designed and coded

FIGURE 16.8
Data management system for a national feed inventory



to accommodate the specific needs of the national feed inventory. For the GIS, open source systems are available; however, the commercial GIS and image analysis packages that are currently available are more robust and can accommodate the mapping and analysis that is required for a national feed inventory. The majority of commercial GIS and image analysis software packages require site licensing, so this cost needs to be factored into the yearly maintenance costs of the system.

16.7.2 Personnel

Having qualified personnel available for working with the database management system will be paramount for successful implementation of a national feed inventory. At a minimum, three people need to be assigned to maintain the system. First, a system administrator with demonstrated experience in managing hardware and software for enterprise databases and web servers is needed. Second, a systems analyst is required for software and web page development and to develop scripting tools for data extraction and retrieval. Third, a GIS specialist is needed for the feed inventory spatial analysis and for developing map products. The data management personnel could be part of a larger information technology (IT) staff, but the majority of their time would need to be dedicated to maintaining the system.

16.8 SUMMARY

A comprehensive quantification of livestock feeds is needed at national level in order for countries to develop policies for maintaining or increasing livestock production and for developing contingencies in the face of drought or other disasters. For rangeland and grassland systems, quantification of forage quantity and quality for feed inventories can be a challenge because of the large land areas that grasslands/rangelands occupy, their remote locations and the diverse mix of livestock species that graze these lands.

For both forage quantity and quality assessment, a number of methods have been developed for measurement of these variables that vary in levels of accuracy, time spent in the field and logistical implementation. For forage quantity measurements, methods include direct measurements of vegetation, estimation with proxy variables, simulation modelling or combinations of these. For forage quality measurement, direct, indirect and estimation with proxy variable methods are available. Logistics, costs, timing of data collection and availability of qualified personnel all influence the choice of method for both forage quantity and quality assessment.

Direct field measurement techniques are the most accurate methods for assessing forage quality on rangelands. However, field techniques generally require a large amount of time and resources for data collection, especially if data collection is required for an entire country on a yearly basis. Field measurement methods for forage biomass include direct measurement techniques where biomass is sampled and weighed, estimation techniques where the biomass weight is estimated by the observer, or combinations of these methods. The most common direct measurement method for measuring forage biomass is the quadrat method where a series of quadrats of known area are clipped, later weighed, and the weights averaged to produce an estimate of forage biomass. Because of the time required for clipping a large number of quadrats, estimation techniques can be used to reduce the number of clipped samples and to reduce sampling time. Two popular methods are the weight unit method and the double sampling method. The weight unit method allows field personnel to visually estimate the majority of the quadrats based on predetermined weight units. The double sampling method combines quadrat clipping with an easily measured variable such as plant cover to develop a statistical equation to predict biomass in unclipped quadrats.

For a national feed inventory that relies on direct measurements or measurements using estimation techniques, a sampling plan needs to be developed that would allow the productivity of the region to be properly represented and provide a means for scaling the results to regional or national levels. GIS software and data layers such as soils, vegetation and roads can assist in stratifying regional and national land areas into representative sampling units. These areas can be delineated in the GIS and provide the means for aggregating to national levels.

Remote-sensing techniques for assessing forage biomass include empirical prediction models and process models that use remote-sensing inputs to predict biomass. Empirical models predict biomass amounts based on a statistical relationship between the biomass and the spectral bands (or combinations of these) from the remote-sensing imagery. Process models based on remote-sensing data generally involve using variables derived from remote-sensing imagery to drive a light use efficiency or similar process model to predict biomass. Regardless of whether empirical or process models are used with remote-sensing information to derive biomass, direct measurement data are generally needed to develop the statistical relationship or to validate the model outputs. Disadvantages of using remote-sensing techniques to predict forage quantity include problems with extrapolating the data to new areas and the inability of the models to predict biomass for specific grazing animals.

Simulation modelling offers unique capabilities for an assessment of forage quantity needed for a national feed inventory programme. Initially, simulation modelling can be time-consuming and expensive for efforts in parameterizing, calibrating and validating the simulation model. However, the capabilities that simulation modelling provides, such as near real-time monitoring, forecasting and exploration of alternatives, makes it an attractive choice for a national feed inventory programme. Several different simulation models are available for estimation of forage biomass on rangelands and grasslands. The choice of model should be driven by the needs of the national feed inventory programme. The models can be integrated with GIS software and other data for improving the spatial relevance of the data and/or extending the simulation model outputs. For a comprehensive analysis of forage biomass production in relation to other ecosystem processes and variables, ecosystem models can be used. The use of ecosystem models in a national feed inventory system provides the ability to holistically examine the processes of forage production and use by livestock and explore specific causes for feed deficits or surpluses. This information can then be used to assist in determining interventions or deciding where improvements can be made in forage production.

For assessments of forage quality, direct measurements generally involve animal observation or the use of research animals that have esophageal or rumen fistulas. Animal observation methods include hand plucking vegetation or bite counting. Both methods can be time-consuming and require the use of relatively tame animals for the field observations. The use of esophageal or rumen fistulated animals is generally accepted as one of the more accurate methods for obtaining forage quality estimates. For this method, research animals are surgically altered by cutting a hole in the esophagus or rumen. A plug is placed in the hole and removed when used for forage quality sampling. Vegetation that falls out of the esophagus or accumulates in the rumen is collected and sampled for quality. Disadvantages of using fistulated animals for forage quality assessment include the need to maintain a special herd of animals that require constant maintenance because of fistulation and the need for highly trained personnel to work with these animals. Because of these issues and the need to sample a large geographic space, the use of fistulated animals to conduct assessments of diet quality for a national feed inventory is generally not practical.

Indirect methods of determining forage quality generally involve examinations of livestock faeces for indicators that can be correlated with the quality of the forage eaten by the grazing animal. Early work on indirect methods involved examination of the constituents of faeces such as faecal nitrogen and fiber components. More recently, the use of Near Infrared Reflectance Spectroscopy (NIRS) scanning of livestock faeces has emerged as a reliable tool for assessing the quality of forage grazed by ruminants. The methodology for developing faecal NIRS (FNIRS) scanning capabilities involves development of reference equations that statistically compare near infrared spectral characteristics of the livestock faeces with quality constituents (e.g. crude protein, digestibility, fiber) of the forage eaten by the livestock. The diet quality information needed for equation development can be gathered from feeding trials using penned animals or from trials using fistulated animals and free-ranging livestock. Advantages of FNIRS are that it provides a rapid and reliable means of assessing the quality of forage the livestock animal is eating, and samples can be easily acquired without destructive harvesting. Disadvantages of FNIRS include the high up-front cost of the NIRS equipment, the need to develop feeding trials and equations that encompass the range of forage types and qualities, and the need for independent validation of the FNIRS equations. For a national feed inventory, FNIRS may be the most practical choice to assess diet quality across a nation. However, the costs of equipment, training of personnel and logistics of gathering faecal samples to represent the region may be prohibitive.

Approaches for using remote-sensing data to estimate forage quality generally involve the development of statistical relationships between remote-sensing spectral band data and forage quality variables such as crude protein and forage digestibility. Several studies have examined these in relation to NDVI derived from remote-sensing imagery to represent vegetation greenness. Other methods include the use of interpolation techniques such as co-kriging that allow mapping of forage quality based on spatial correlations between forage quality variables and remote-sensing data such as NDVI. The forage quality data are collected at representative locations throughout a region and co-kriging with NDVI data allows interpolation of the quality data so that landscape maps of forage quality can be produced.

Terrain factors such as slope and shrub/tree density along with distance to water can influence the availability of biomass for livestock grazing, but the degree to which these factors influence availability is dependent on the kind of livestock. Slopes greater than 45 percent are hard to access by most livestock so considerations should be made about the usability of vegetation in areas of steep slopes. Very rocky areas or areas of dense shrubs and trees can also limit the ability of cattle to graze the vegetation in these areas. However, sheep and goats can generally navigate these areas because of smaller body and hoof sizes.

Distance to water also influences the availability or usability of forage in a region. Cattle need water every day for efficient growth so they generally do not travel more than 3.2 km from water unless they are herded. Sheep and goats can graze at much longer distances from water sources because they do not need to water each day. For a feed inventory in areas with large distance between water sources, corrections may be needed to reduce forage allocations for some grazing livestock.

Since livestock production on grasslands and rangelands is a significant contribution to the overall GDP in many countries and is a component of the wealth and well-being of many people, especially pastoralists, the assessment of animal production as it is related to forage quantity and quality is important for monitoring at the national or regional level. The development of a national feed inventory for assessing forage biomass provides the opportunity to assess production capacity through an assessment of stocking rates. The inventory of forage quality information can be used improve livestock production and feed management through nutritional balancing. It can also be used to assess supplemental feed requirements for enhancing/maintaining production and optimal strategies for supplemental feeding during rangeland forage shortages.

For a national feed inventory programme to be successfully implemented, data management and quality control system infrastructure will be needed. A tremendous amount of data will need to be acquired, and therefore a data management plan will need to be developed at the inception of the programme that outlines how data will be collected, how and where it will be stored, and methods for data access. A centralized database system with a portal for entering field data and a web portal for data extraction and visualization provides usability and flexibility in the system. Linking the database to a GIS allows mapping and spatial analysis of data that can be displayed via a mapping portal or integrated into the web portal. Qualified IT personnel are needed to support the database management system and ensure that quality control is maintained.

16.9 REFERENCES

Al-Bakri, J. T. & Taylor, J. C. 2003. Application of NOAA AVHRR for monitoring vegetation conditions and biomass in Jordan. *J. Arid Environ.,* 54(3): 579–593.

Allen, V. G. & Segarra, E. 2001. Anti-quality components in forage: Overview, significance, and economic impact. *J. Range Manag.,* 54(4): 409–412.

Angerer, J. P. 2008. *Examination of high resolution rainfall products and satellite greenness indices for estimating patch and landscape forage biomass*. Texas A&M University, College Station, Texas. USA.129 pp (PhD Thesis).

Asrar, G., Fuchs, M., Kanemasu, E. T. & Hatfield, J. L. 1984. Estimating absorbed photosynthetic radiation and leaf area index from spectral reflectance in wheat. *Agron. J.,* 76: 300–306.

Awuma, K. S., Stuth, J. W., Kaitho, R. & Angerer, J. 2007. Application of normalized differential Vegetation Index and geostatistical techniques in cattle diet quality mapping in Ghana. *Outlook Agric.,* 36(3): 205–213.

Bolor-Erdene, L., Angerer J., Granville-Ross S., Urgamal M., Narangarel D., Tsogoo D., Stewart T. & Sheehy, D. 2008. Gobi Forage: An early warning system for livestock in the Gobi region of Mongolia. In: *Joint Meeting of the 21st International Grassland Congress and the 8th International Rangeland Congress*. Hohhot, China.

Bonhan, C.D. 1989. Measurements for terrestrial vegetation. Wiley, New York, 338p

Boone, R.B. & Wang, G. 2007. Cattle dynamics in African grazing systems under variable climates. *J. Arid Environ.*, 70(3): 495–513.

Brown, J. R. & Thorpe, J. 2008. Climate change and rangelands: Responding rationally to uncertainty. *Rangelands*, 30(3): 3–6.

Bouraoui, F., Wolfe, M.L., 1990. Application of hydrologic models to rangelands. *J. Hydrol.* 121, 173-191.

Brown, M.E., Pinzon, J. E., Didan, K., Morisette, J.T. & Tucker, C.J. 2006. Evaluation of the consistency of long-term NDVI time series derived from AVHRR, SPOT-Vegetation, SeaWiFS, MODIS, and Landsat ETM+ sensors. *IEEE Trans. Geosci. Remote Sens.*, 44(7): 1787–1793.

Carlson D.H. &Thurow T.L. 1992. *SPUR-91: Workbook and User Guide*. Texas A&M University, Department of Rangeland Ecology and Management in cooperation with USDA Soil Conservation Service. College Station, TX Pub. No. MP-1743. pp. 259.

Catchpole, W.R. & Wheeler, C.J. 1992. Estimating plant biomass: A review of techniques. *Australian J. Ecol.*, 17(2): 121–131.

Childress, W.M., Coldren, C. L. & McLendon, T. 2002. Applying a complex, general ecosystem model (EDYS) in large-scale land management. *Ecol. Model.*, 153: 97–108.

Christensen, L., Coughenour, M. B., Ellis, J.E. & Chen, Z.Z. 2003. Sustainability of inner Mongolian grasslands: Application of the Savanna model. *J. Range Manag.*, 56(4): 319–327.

Coughenour, M.B. 1993. *SAVANNA – A Spatial ecosystem model. Model description and user guide*. Natural Resources Ecology Laboratory, Colorado State University,Fort Collins, Colorado, USA 64 pp. Available at www.nrel.colostate.edu/projects/savanna/.

Coughenour, M.B. 1999. *Ecosystem modelling of the Pryor Mountain Wild Horse Range*. Report to USGS. Biological Resources Division, National Park Service, and Bureau of Land Management. 55 pp. & 100 Figs. Available at www.nrel.colostate.edu/projects/savanna/.

Coughenour, M.B. 2002. *Elk in the Rocky Mountain National Park Ecosystem – A model-based assessment*. Final report to USGS Biological Resources Division, Ft. Collins, Colorado and U.S. National Park Service, Rocky Mountain National Park. 125 pp. 116 Figs. Available at www.nrel.colostate.edu/projects/savanna/.

Coughenour, M.B. 2005. *Spatial modelling of Yellowstone Bison and their environments*. Final Report to U.S. Geological Survey, Biological Resources Division, Bozeman, MT, USA. (Three-part report. 93 pp. 100 figures & 73 tables. Available at www.nrel.colostate.edu/projects/savanna/.

Cracknell, A.P. 2001. The exciting and totally unanticipated success of the AVHRR in applications for which it was never intended. *Adv. Space Res.*, 28(1): 233–240.

Decruyenaere, V., Buldgen, A. & Stilmant, D. 2009. Factors affecting intake by grazing ruminants and related quantification methods: a review. *Biotechnol. Agron. Soc. et Environ.*, 13(4): 559–573.

Devries, M.F.W. 1995. Estimating forage intake and quality in grazing cattle - a reconsideration of the hand-plucking method. *J.Range Manag.*, 48(4): 370–375.

Dixon, R. & Coates, D. 2009. Review: Near infrared spectroscopy of faeces to evaluate the nutrition and physiology of herbivores. *J.Near Infrared Spectros.*, 17(1): 1–31.

Dixon, R.M. & Coates, D.B. 2010. Diet quality estimated with faecal near infrared reflectance spectroscopy and responses to N supplementation by cattle grazing buffel grass pastures. *Anim. Feed Sci. Technol.*, 158(3–4): 115–125.

Dungan, J. 1998. Spatial prediction of vegetation quantities using ground and image data. International *J. Remote Sens.*, 19(2): 267–285.

Ellis, J.E. & Coughenour, M.B. 1998. The SAVANNA integrated modelling system: an integrated remote sensing, GIS and spatial simulation modelling approach. *In* V. R. Squires & A. E. Sidahmed, eds. *Drylands: Sustainable use of rangelands into the twenty-first century*s. IFAD Series Technical Report. pp. 97–106.

Espach, C., Lubbe, L.G. & Ganzin, N. 2009. Determining grazing capacity in Namibia with the aid of remote sensing. *African J. Range Forage Sci.*, 26(3): 133–138.

Fales, S.L. & Fritz, J.O. 2007. Factors affecting forage quality. *In* R. F. Barnes, D. A. Miller & C. J. Nelson, eds. pp. 569–580. *Forages, Volume 2: The Science of Grassland Agriculture*. Ames, Iowa. Blackwell Publishers, USA.

Flanagan, D.C. & Nearing, M.A. 1995. *WEPP technical documentation*. National Soil Erosion Research Lab, West Lafayette, Indiana, USA.

Foody, G. M. 2003. Geographical weighting as a further refinement to regression modelling: An example focused on the NDVI–rainfall relationship. *Remote Sens. Environ.*, 88: 283–293.

Foy, J.K., Teague, W.R. & Hanson, J.D. 1999. Evaluation of the upgraded SPUR model (SPUR2.4). *Ecol. Modelling*, 118(2–3): 149–165.

Frank, A.B. & Karn, J.F. 2003. Vegetation indices, CO_2 flux, and biomass for Northern Plains grasslands. *J. Range Manag.*, 56(4): 382–387.

Ganskopp, D. & Bohnert, D. 2006. Do pasture-scale nutritional patterns affect cattle distribution on rangelands? *Rangeland Ecol. Manag.*, 59(2): 189–196.

Gitelson, A.A. 2004. Wide dynamic range vegetation index for remote quantification of biophysical characteristics of vegetation. *J. Plant Physiol.*, 161(2): 165–173.

Glasser, T., Landau, S., Ungar, E.D., Perevolotsky, A., Dvash, L., Muklada, H., Kababya, D. & Walker, J. W. 2008. A fecal near-infrared reflectance spectroscopy-aided methodology to determine goat dietary composition in a Mediterranean shrubland. *J. Anim. Sci.*, 86(6): 1345–1356.

Gordon, I.J. 1995. Animal-based techniques for grazing ecology research. *Small Rumin., Res.*,16(3): 203–214.

Hanson J.D., Baker B.B. & Bourdon R.M. 1992. *SPUR2 documentation and user guide*. GPSR technical report No. 1. pp. 24. US Dept. of Agric. USA.

Herrick, J., Van Zee, J., Havstad, K., Burkett, L. & Whitford, W. 2005. *Monitoring manual for grassland, shrubland, and Savanna ecosystems, Vol II. Design, supplementary methods and interpretation*. USDA Jornada Experimental Range. University of Arizona Press, Tuscon AZ, USA. pp. 236.

Hirschfeld, D.J., Kirby, D.R., Caton, J.S., Silcox, S.S. & Olson, K.C. 1996. Influence of grazing management on intake and composition of cattle diets. *J. Range Manag.*, 49(3): 257–263.

Hohlt, J.C., Lyons, R.K., Hanselka, C.W. & McKown, D. 2009. *Estimating grazeable acreage for cattle*. Texas AgriLife Extension Service, College Station, TX. Texas AgriLife Extension Publication B-6222, USA.

Holecheck, J.L., Vavra, M. & Pieper, R.D. 1982. Methods for determining the nutritive quality of range ruminant diets: A review. *J. Anim. Sci.,* 54(2): 363–376.

Holechek, J., Pieper, R.D. & Herbel, C.H. 2001. *Range Management: Principles and Practices*. Prentice Hall, Upper Saddle River, N.J., USA.

Holechek, J.L., Vavra, M. & Arthun, D. 1982. Relationships between performance, intake, diet nutritive quality and fecal nutritive quality of cattle on mountain range. *J. Range Manag.*, 35(6): 741–744.

Huete, A., Didan, K., Miura, T., Rodriguez, E.P., Gao, X. & Ferreira, L.G. 2002. Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sens. Environ.*, 83(1–2): 195–213.

Hunt, E.R. & Miyake, B.A. 2006. Comparison of stocking rates from remote sensing and geospatial data. *Rangeland Ecol. Manag.*, 59(1): 11–18.

Hurcom, S.J. & Harrison, A.R. 1998. The NDVI and spectral decomposition for semi-arid vegetation abundance estimation. *Int. J. Remote Sens.*, 19(16): 3109–3125.

Isaaks, E.H. & Srivastava, R.M. 1989. *Applied geostatistics*. Oxford University Press, New York, USA.

Kawamura, K., Akiyama, T., Yokota, H., Tsutsumi, M., Yasuda, T., Watanabe, O., Wang, G. & Wang, S. 2005. Monitoring of forage conditions with MODIS imagery in the Xilingol steppe, Inner Mongolia. *Int. J. Remote Sens.*, 26(7): 1423–1436.

Kiesling, H.E., Nelson, A.B. & Herbel, C.H. 1969. Chemical composition of tobosa grass collected by hand-plucking and esophageal-fistulated steers. *J. Range Manag.*, 22(3): 155–159.

Kiniry, J.R., Sanchez, H., Greenwade, J., Seidensticker, E., Bell, J.R., Pringle, F., Peacock, G. & Rives, J. 2002. Simulating grass productivity on diverse range sites in Texas. *J. Soil Water Conser.*, 57(3): 144–150.

Kogan, F., Stark, R., Gitleson, A., Jargalsaikhan, C., Dugrajav, C. & Tsooj, S. 2004. Derivation of pasture biomass in Mongolia from AVHRR-based vegetation health indices. *Int. J. Remote Sens.*, 25(14): 2889–2896.

Langlands, J.P. 1974. Studies on the nutritive value of the diet selected by grazing sheep VII. A note on hand plucking as a technique for estimating dietary composition. *Anim. Sci.*, 19(02): 249–252.

Leite, E.R. & Stuth, J.W. 1995. Fecal NIRS equations to assess diet quality of free-ranging goats. *Small Rumin. Res.*, 15(3): 223–230.

Li, H., Tolleson, D., Stuth, J., Bai, K., Mo, F. & Kronberg, S. 2007. Faecal near infrared reflectance spectroscopy to predict diet quality for sheep. *Small Rumin. Res.*, 68(3): 263–268.

Lyons, R.K. & Stuth, J.W. 1992. Fecal NIRS equations for predicting diet quality of free-ranging cattle. *J. Range Manag.*, 45(3): 238–244.

Mata, M., Clark, D. A., Edirisinghe, A., Waugh, D., Minneé, E. & Gherardi, S.G. 2007. Predicting accurate paddock average pasture cover in Waikato dairy farms using satellite images. *Proc. 69th Annual NZ Grassland Assoc. Conf.*, 69: 23–28.

McDaniel, K.C. & Tiedeman, J.A. 1981. Sheep use on mountain winter range in New Mexico. *J. Range Manag.*, 34(2): 102–104.

Montieth, J.L. 1972. Solar radiation and productivity in tropical ecosystems. *Appl. Ecol.*, 9: 747–766.

Montieth, J.L. 1977. Climate and efficiency of crop production in Britian. *Philosophical Trans. Royal Soc.London, Series B*, 281: 277–294.

Ortega, I.M., SolteroGardea, S., Drawe, D. L. & Bryant, F. C. 1997. Evaluating grazing strategies for cattle: Nutrition of cattle and deer. *J. Range Manag.*, 50(6): 631–637.

Owens, M.K., Launchbaugh, K.L. & Holloway, J.W. 1991. Pasture characteristics affecting spatial distribution of utilization by cattle in mixed brush communities. *J. Range Manag.*, 44(2): 118–123.

Pfister, J.A., Hansen, D. & Malechek, J.C. 1990. Surgical establishment and maintenance of esophageal fistulae in small ruminants. *Small Rumin. Res.*, 3(1): 47–56.

Pierson, F.B., Carlson, D. H. & Spaeth, K.E. 2001. A process-based hydrology submodel dynamically linked to the plant component of the simulation of production and utilization on rangelands SPUR model. *Ecol. Modelling*, 141(1–3): 241–260.

Plumb, G.E., White, P. J., Coughenour, M.B. & Wallen, R.L. 2009. Carrying capacity, migration, and dispersal in Yellowstone bison. *Biol. Cons.*, 142(11): 2377–2387.

Quirk, M.F. & Stuth, J.W. 1995. Preference-based algorithms for predicting herbivore diet composition. *Ann. Zootech.*, 44: 110.

Reeves, M.C., Winslow, J.C. & Running, S.W. 2001. Mapping weekly rangeland vegetation productivity using MODIS algorithms. *J. Range Manag.*, 54: A90–A105.

Rouse, J.W., Haas, R. H., Schell, J.A. & Deering, D.W. 1973. Monitoring vegetation systems in the Great Plains with ERTS. In *Proceedings of the third ERTS Symposium*, *Vol. 1*, pp. 309–317 Washington DC, USA.

Ryan, Z. 2005. *Establishment and evaluation of a livestock early warning system for Laikipia, Kenya*. Texas A&M University: College Station, Texas, USA (PhD Thesis).

Sannier, C.A.D., Taylor, J.C. & Du Plessis, W. 2002. Real-time monitoring of vegetation biomass with NOAA-AVHRR in Etosha National Park, Namibia, for fire risk assessment. *Int. J. Remote Sens.*, 23(1): 71–89.

Sellers, P.J. 1985. Canopy reflectance, photosynthesis and transpiration. *International J. Remote Sens.*, 6: 1335–1372.

Showers, S.E., Tolleson, D.R., Stuth, J.W., Kroll, J.C. & Koerth, B.H. 2006. Predicting diet quality of white-tailed deer via NIRS fecal profiling. *Rangeland Ecol. Manag.*, 59(3): 300–307.

Squires, V. & Siebert, B. 1983. Botanical and chemical components of the diet and liveweight change in cattle on semi-desert rangeland in central Australia. *The Rangeland J.,* 5(1): 28–34.

Stuth, J.W., Angerer, J., Kaitho, R., Zander, K., Jama, A., Heath C., Bucher, J., Hamilton, W., Conner, R., & Inbody, D. 2003a. The Livestock Early Warning System (LEWS): Blending technology and the human dimension to support grazing decisions. Arid Lands Newsletter, University of Arizona, USA. Available at http://cals.arizona.edu/OALS/ALN/aln53/stuth.html.

Stuth, J.W., Angerer, J., Kaitho, R., Jama, A. & Marambii, R. 2005. Livestock early warning system for Africa rangelands. *In* V. K. Boken, A. P. Cracknell & R. L. Heathcote, eds. Monitoring and predicting agricultural drought: A global study. Oxford University Press. New York, USA. pp. 472.

Stuth, J.W., Schmitt, D., Rowan, R.C., Angerer, J.P., & Zander, K. 2003b. *PHYGROW users guide and technical documentation*. Texas A&M University, USA.

Teague, W.R. & Foy, J.K. 2002. Validation of SPUR2.4 rangeland simulation model using a cow-calf field experiment. *Agric. Syst.*, 74(2): 287–302.

Thoma, D.P., Bailey, D.W., Long, D.S., Nielsen, G.A., Henry, M.P., Breneman, M.C. & Montagne, C. 2002. Short-term monitoring of rangeland forage conditions with AVHRR imagery. *J. Range Manag.*, 55(4): 383–389.

Thornton, P.K., BurnSilver, S.B., Boone, R.B. & Galvin, K.A. 2006. Modelling the impacts of group ranch subdivision on agro-pastoral households in Kajiado, Kenya. *Agric. Syst.*, 87(3): 331–356.

Timmons, G.R., Hewitt, D. G., DeYoung, C. A., Fulbright, T.E. & Draeger, D.A. 2010. Does supplemental feed increase selective foraging in a browsing ungulate? *J. Wildlife Manag.*, 74(5): 995–1002.

Tucker, C.J. 1979. Red and photographic infrared linear combinations for monitoring vegetation. *Remote Sens. Environ.*, 8(2): 127–150.

Tucker, C.J., Pinzon, J.E., Brown, M.E., Slayback, D.A., Pak, E.W., Mahoney, R., Vermote, E. F. & El Saleous, N. 2005. An extended AVHRR 8-km NDVI dataset compatible with MODIS and SPOT vegetation NDVI data. *Int. J. Remote Sens.*, 26(20): 4485–4498.

Tucker, C.J., Vanpraet, C., Boerwinkel, E. & Gaston, A. 1983. Satellite remote-sensing of total dry-matter production in the Senegalese Sahel. *Remote Sens. Environ.*, 13(6): 461–474.

USDA (United States Department of Agriculture, Natural Resources Conservation Service). 2003. *National Range and Pasture Handbook*. U.S. Dept. of Agriculture, Natural Resources Conservation Service, Grazing Lands Technology Institute. Fort Worth, Texas, USA.

Van Soest, P.J. 1994. *Nutritional Ecology of the Ruminant*. Comstock Publication. Ithaca, New York, USA.

Weisberg, P.J., M.B. Coughenour, M.NB. & Bugmann, H. 2006. Modelling of large herbivore-vegetation interactions in a landscape context. Chapter 12 *In* K. Danell, R. Bergstrom, P. Duncan & J. Pastor, eds. Large Herbivore Ecology, Ecosystem Dynamics and Conservation. Cambridge Univ. Press, Cambridge, UK.

White, I.A., Hunt, L.P., Poppi, D.P. & Petty, S.R. 2010. Sampling requirements for predicting cattle diet quality using faecal near-infrared reflectance spectroscopy (F.NIRS) in heterogeneous tropical rangeland pastures. *Rangeland J.*, 32(4): 435–441.

Wight, J.R. & Skiles, J.W. 1987. *SPUR: Simulation and production and utilization of rangelands. Documentation and user's guide.* United States Department of Agriculture, Agricultural Research Service, USA. pp. 372.

Williams, J.R., Izaurralde, R.C. & Steglich, E.M. 2008. *Agricultural policy/environmental extender model: Theoretical documentation, Version 0604*. Blackland Research and Extension Center, Texas AgriLife Research, Texas A& M University Temple, Texas, USA.

Wofford, H., Holechek, J. L., Galyean, M.L., Wallace, J.D. & Cardenas, M. 1985. Evaluation of fecal indices to predict cattle diet quality. *J. Range Manag.*, 8(5): 450–454.

FAO ANIMAL PRODUCTION AND HEALTH MANUALS

1. Small-scale poultry production, 2004 (E, F)
2. Good practices for the meat industry, 2006 (E, F, S, Ar)
3. Preparing for highly pathogenic avian influenza, 2006 (E, Ar, S[e], F[e], M[e])
3. Revised version, 2009 (E)
4. Wild bird HPAI surveillance – a manual for sample collection from healthy, sick and dead birds, 2006 (E, F, R, Id, Ar, Ba, S[e], C[e],)
5. Wild birds and avian influenza – an introduction to applied field research and disease sampling techniques, 2007 (E, F, R, Ar, Id, Ba, S**)
6. Compensation programs for the sanitary emergence of HPAI-H5N1 in Latin American and the Caribbean, 2008 (E[e], S[e])
7. The AVE systems of geographic information for the assistance in the epidemiological surveillance of the avian influenza, based on risk, 2009 (E[e], S[e])
8. Preparation of African swine fever contingency plans, 2009 (E, F, R, Hy, Ka, S[e])
9. Good practices for the feed industry – implementing the Codex Alimentarius Code of Practice on good animal feeding, 2009 (E, Ar, C**, F**, S**, P**)
10. Epidemiología Participativa – Métodos para la recolección de acciones y datos orientados a la inteligencia epidemiológica, 2011 (S[e])
11. Good Emergency Management Practices: The essentials, 2011 (E)
12. Investigating the role of bats in emerging zoonosese – Balancing ecology, conservation and public health interests, 2011 (E)
13. Rearing young ruminants on milk replacers and starter feeds, 2011 (E)
14. Quality assurance for animal feed analysis laboratories, 2011 (E)
15. Conducting national feed assessments, 2012 (E)

Availability: September 2012

Ar	–	Arabic	Multil	–	Multilingual
C	–	Chinese	*		Out of print
E	–	English	**		In preparation
F	–	French	e		E-publication
P	–	Portuguese			
R	–	Russian			
S	–	Spanish	Ba	–	Bangla
M	–	Mongolian	Hy	–	Armenian
Id	–	Bahasa	Ka	–	Georgian

The *FAO Animal Production and Health Manuals* are available through the authorized FAO Sales Agents or directly from Sales and Marketing Group, FAO, Viale delle Terme di Caracalla, 00153 Rome, Italy.

FAO ANIMAL HEALTH MANUALS

1. Manual on the diagnosis of rinderpest, 1996 (E)
2. Manual on bovine spongifom encephalophaty, 1998 (E)
3. Epidemiology, diagnosis and control of helminth parasites of swine, 1998
4. Epidemiology, diagnosis and control of poultry parasites, 1998
5. Recognizing peste des petits ruminant – a field manual, 1999 (E, F)
6. Manual on the preparation of national animal disease emergency preparedness plans, 1999 (E)
7. Manual on the preparation of rinderpest contingency plans, 1999 (E)
8. Manual on livestock disease surveillance and information systems, 1999 (E)
9. Recognizing African swine fever – a field manual, 2000 (E, F)
10. Manual on participatory epidemiology – method for the collection of action-oriented epidemiological intelligence, 2000 (E)

11. Manual on the preparation of African swine fever contigency plans, 2001 (E)
12. Manual on procedures for disease eradication by stamping out, 2001 (E)
13. Recognizing contagious bovine pleuropneumonia, 2001 (E, F)
14. Preparation of contagious bovine pleuropneumonia contingency plans, 2002 (E, F)
15. Preparation of Rift Valley fever contingency plans, 2002 (E, F)
16. Preparation of foot-and-mouth disease contingency plans, 2002 (E)
17. Recognizing Rift Valley fever, 2003 (E)

Find more publications at
http://www.fao.org/ag/againfo/resources/en/publications.html

A National Feed Assessment System (NFAS) is a complete set of procedures, facilities, tools, personnel, organizations, and institutions involved in the collecting, handling, processing of data necessary to calculate and report the supplies of livestock feeds from all sources and for all livestock types in a country. It is comprised of numerous components which interact in an integrated manner to achieve a common outcome, the National Feed Assessment (NFA). A NFA is a data- and computation-based analysis of the supplies and demands for livestock feeds in a country.

Accurate assessments of current and future supplies and demands for livestock feed are needed for national food security policy and planning, as well as the setting of environmentally sustainable stocking rates. Feed resources must be assessed and monitored to provide information for the development and implementation of policies that will contribute to the sustainable growth of national livestock sectors. Assessments will provide information on feed resource availabilities that will enable optimal policy decisions regarding the use of national feed resources.

This document provides guidance to countries in developing NFASs. Members of governments and research organizations who wish to establish NFASs will likely seek guidance on the technical issues and procedural aspects of building and institutionalizing NFASs. A set of recommended step-wise procedures is given for implementing NFASs, including procedures for planning, establishing, and updating a NFAS. It is hoped that using the information provided in this document countries will initiate activities to establish and maintain the NFA.

ISBN 978-92-5-107332-2 ISSN 1810-1119

9 789251 073322

I3043E/1/09.12